

Estimation and Initialization of Multi-Decadal Oceanic Variability within The GFDL Coupled Ensemble Data Assimilation System

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Motivations of Ocean Analyses Using Models and Data:

- ✓ One side: facts -
 - Climate model: inevitable drift from reality due to incomplete understanding of climate change and its modeling
 - Observations: inevitable instrument and representation errors

- ✓ The other side: we need -
 - Analysis of climate variability (Carbon/heat uptake, circulation, ...)
 - Detection of climate change
 - Observing system evaluation/design
 - Forecast initialization (SI, decadal)
 - Model evaluation, forecast verification
 - Model parameter estimation

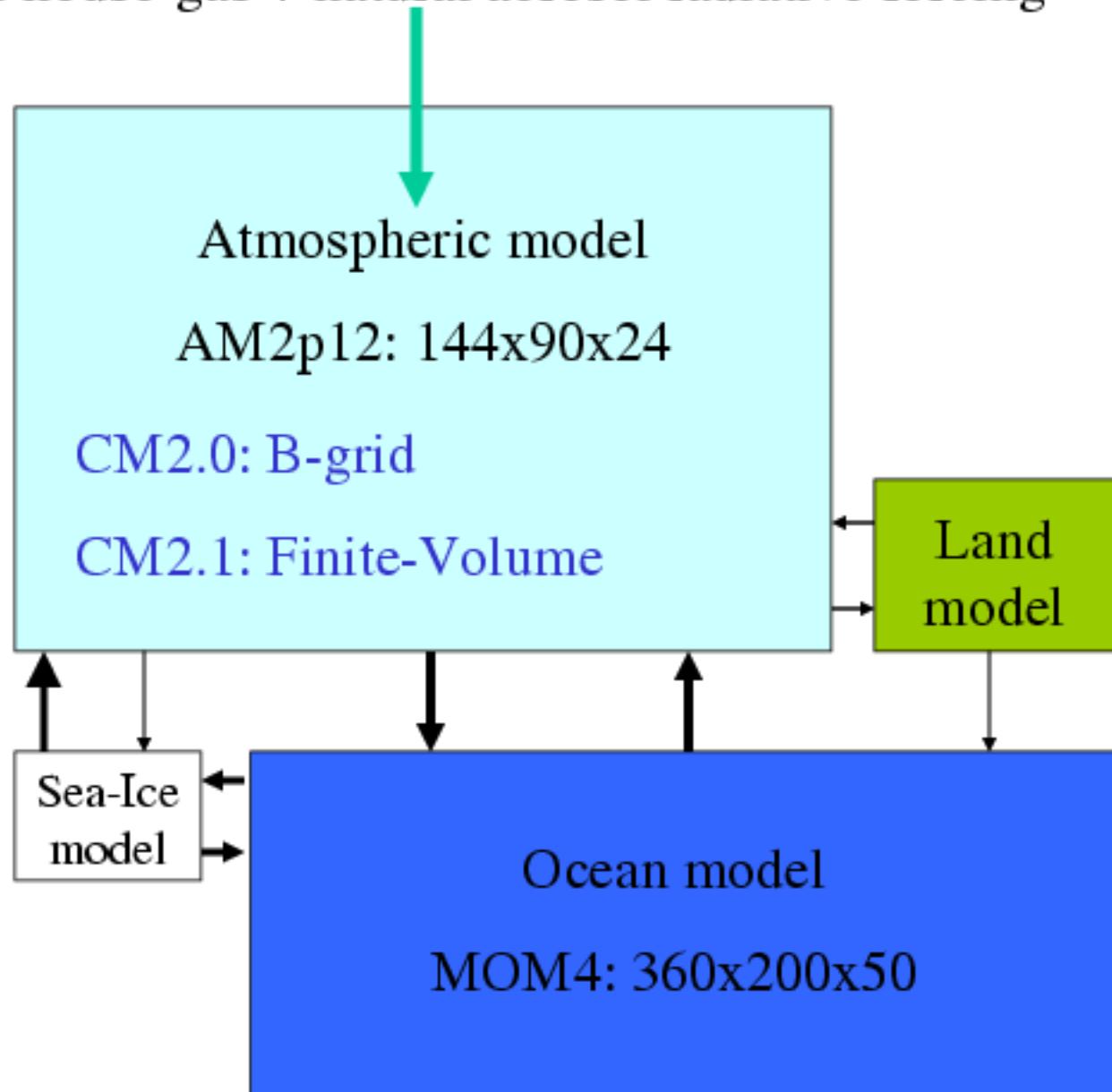
What Good is Coupled Ensemble Data Assimilation for climate studies?

- ✓ A **coupled ensemble** data assimilation system estimates a temporally-evolving ***joint-distribution (Joint-PDF)*** of climate states under observational data constraint, with:
 - Multi-variate analysis scheme maintaining **physical balances** among state variables mostly
 - T-S relationship in ODA
 - Geostrophic balance in ADA
 - Ensemble filter maintaining properties of high order moments of error statistics (nonlinear evolution of errors) mostly
- ✓ Optimal ensemble initialization given data and model dynamics:
 - All coupled components are adjusted by data through exchanged fluxes
 - No initial shocks for numerical climate forecasts

OUTLINE

- ✓ **Introduction of the GFDL's coupled ensemble data assimilation system (MWR 2007)**
- ✓ Perfect model study ‘twin’ experiments: Impact of oceanic observing system (JGR – Oceans 2007)
- ✓ Imperfect model study ‘twin’ experiments: Impact of model biases (MWR in press)
- ✓ Climate estimate for the 20th- and 21st-centuries:
Assimilating the really-observed atmospheric/oceanic data into coupled ensemble system

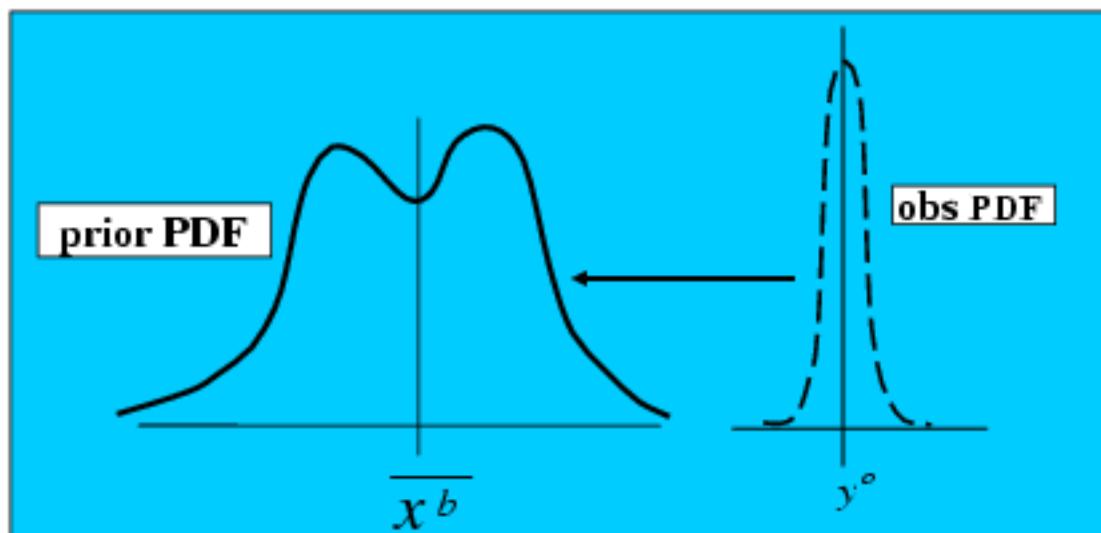
green-house-gas + natural aerosol radiative forcing



Deterministic (being modeled)

$$\frac{d\mathbf{x}_t}{dt} = f(\mathbf{x}_t, t) + \mathbf{G}(\mathbf{x}_t, t)\mathbf{w}_t$$

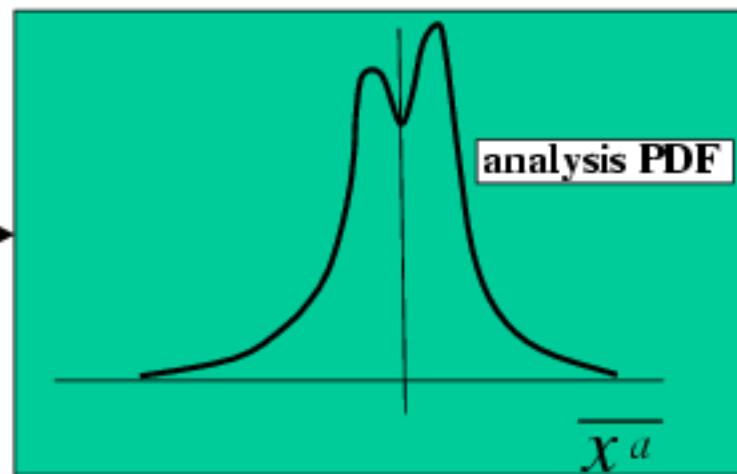
Uncertain (stochastic)



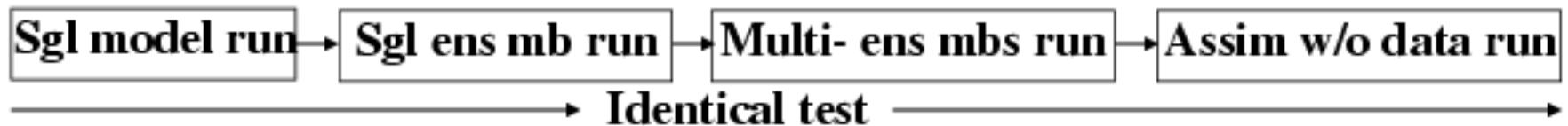
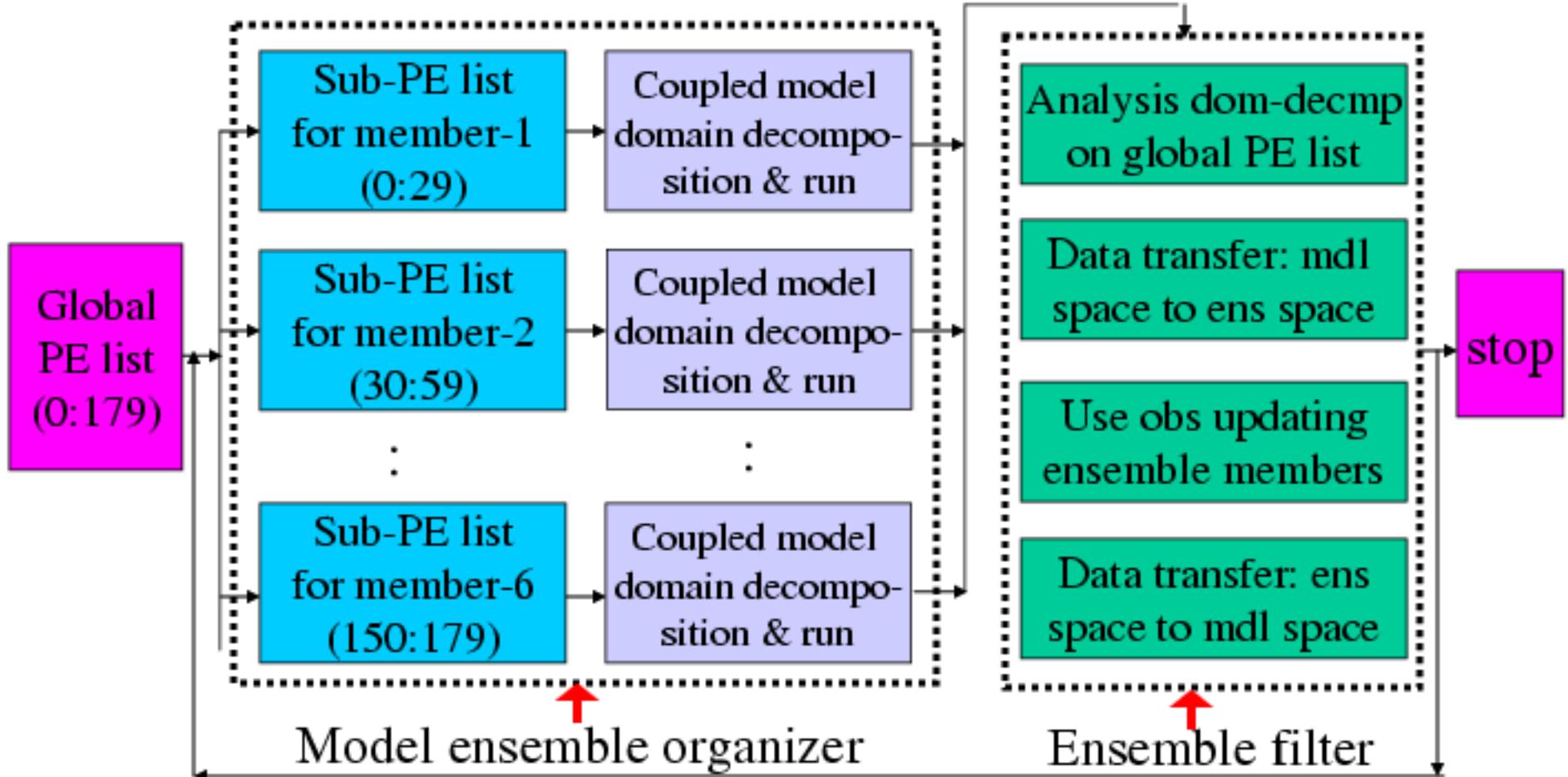
✓ Atmospheric internal variability

✓ Ocean internal variability
(model does not resolve yet)

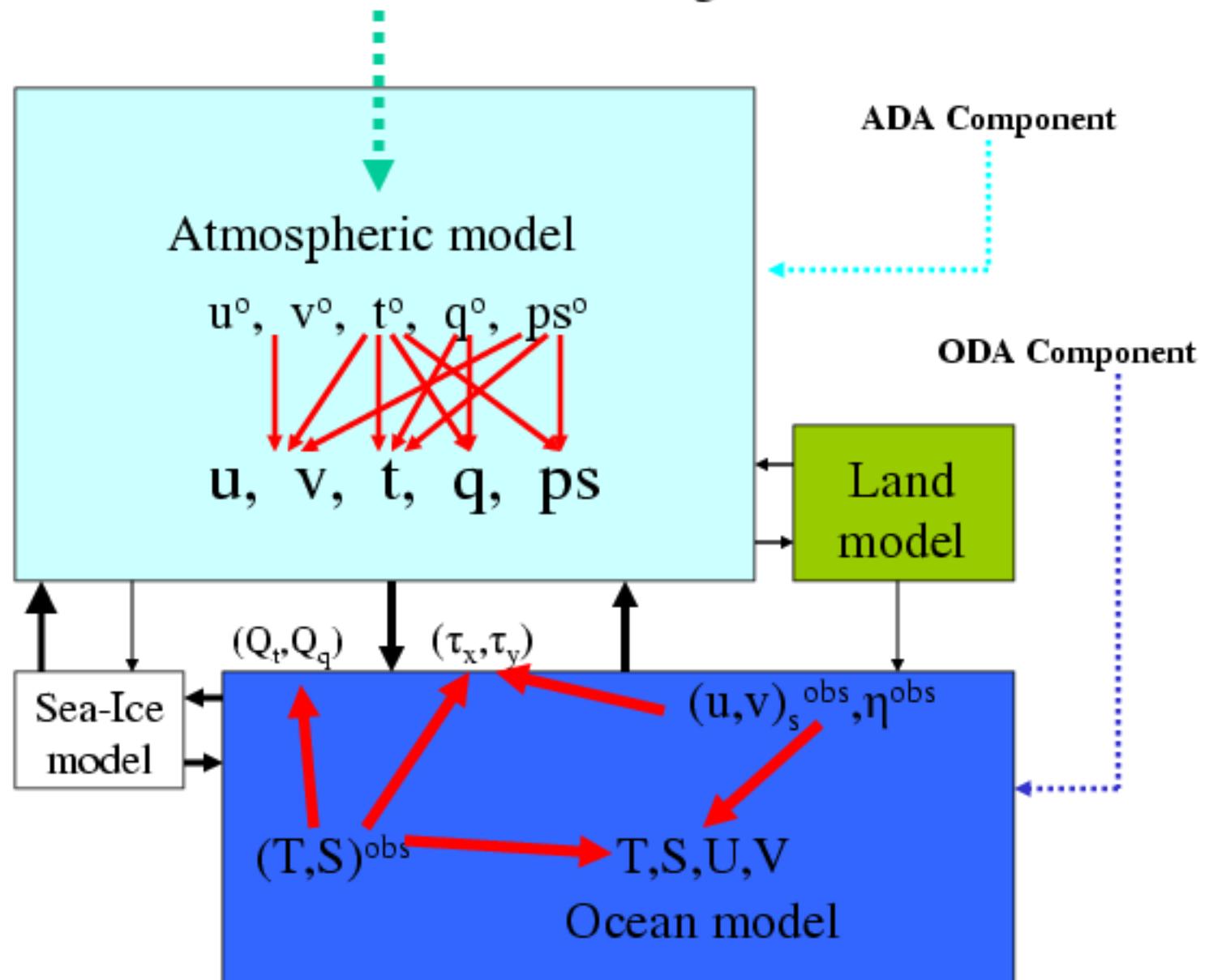
Data Assimilation (Filtering)



CM2 ensemble filter: PE grouping and domain decomposition



GHG + NA radiative forcing



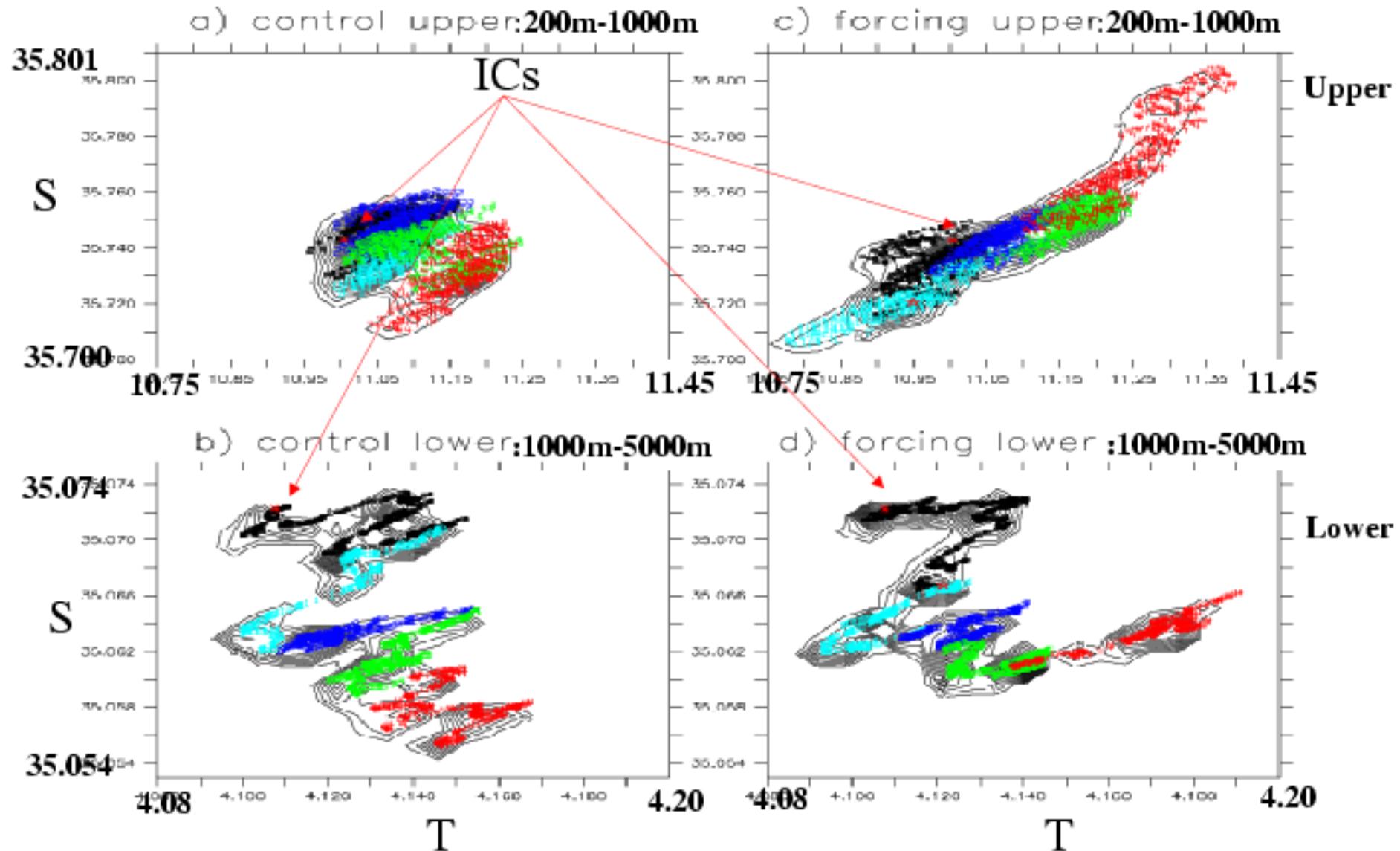
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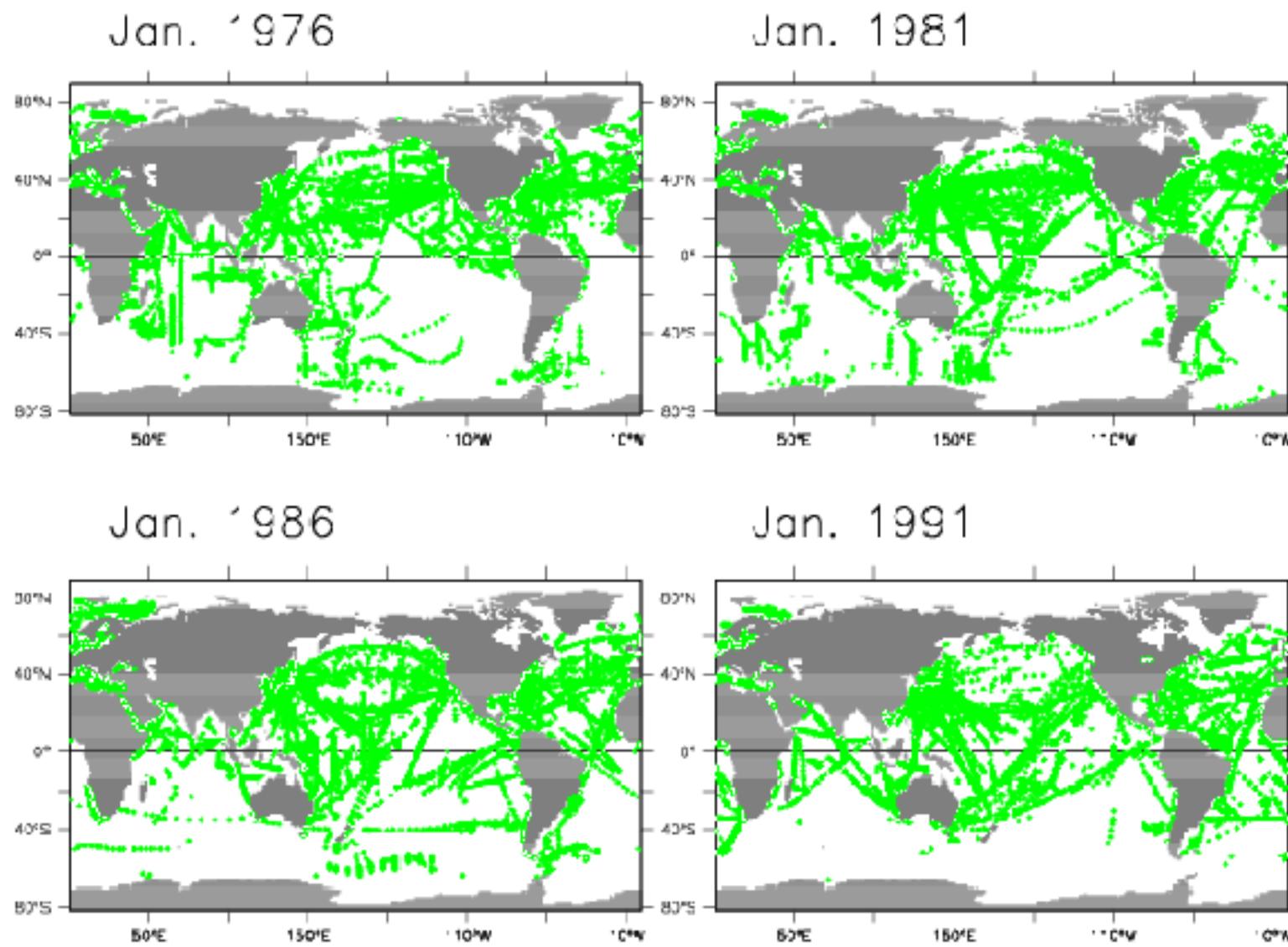
1861-1900
 1901-1925
 1926-1950
 1951-1975
 1976-2000

North Atlantic Temp and Salt in CM2

1860 (fixed-year GHGNA) control run historical (GHGNA) run

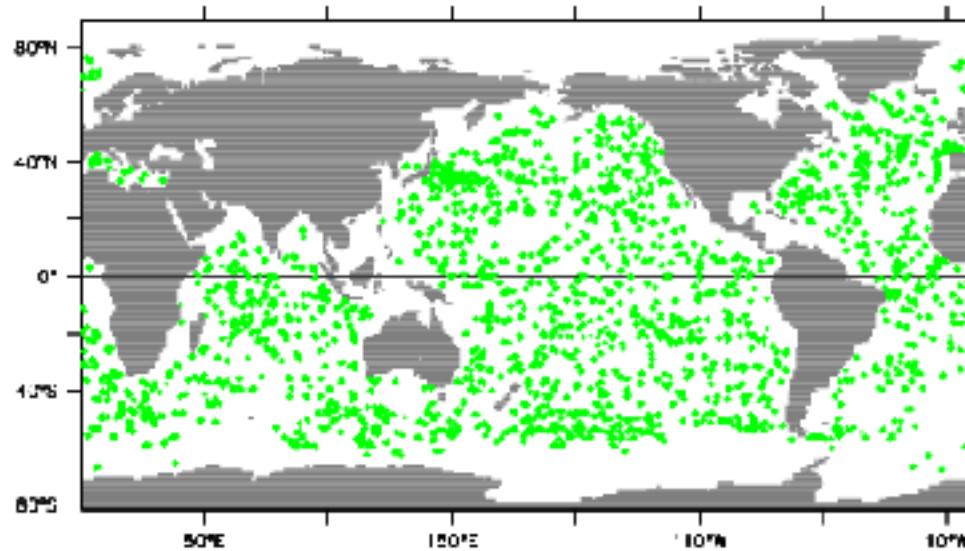


Given ocean temperature observational network
Can we assess climate change in the 20th Century?

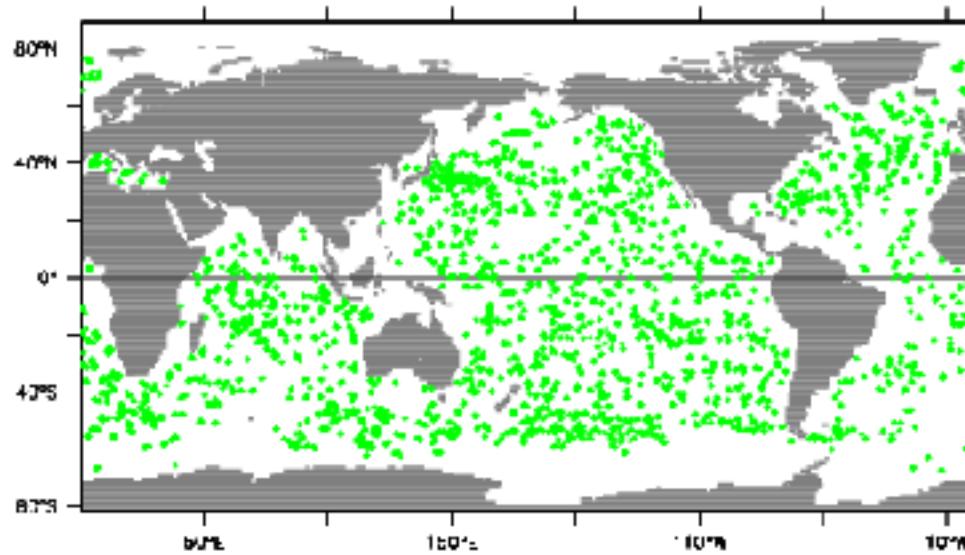


2005 June Argo network

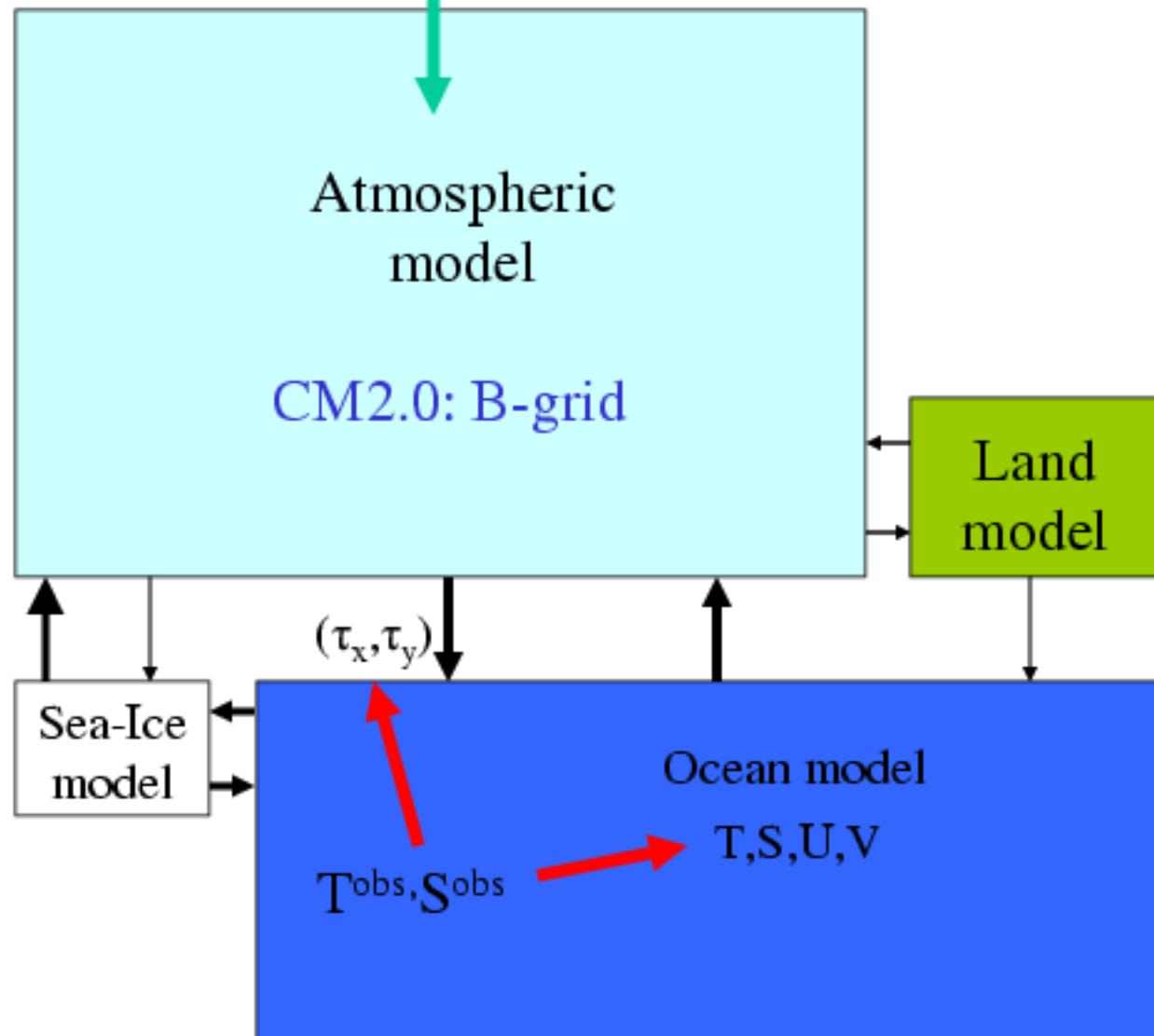
Temperature



Salinity

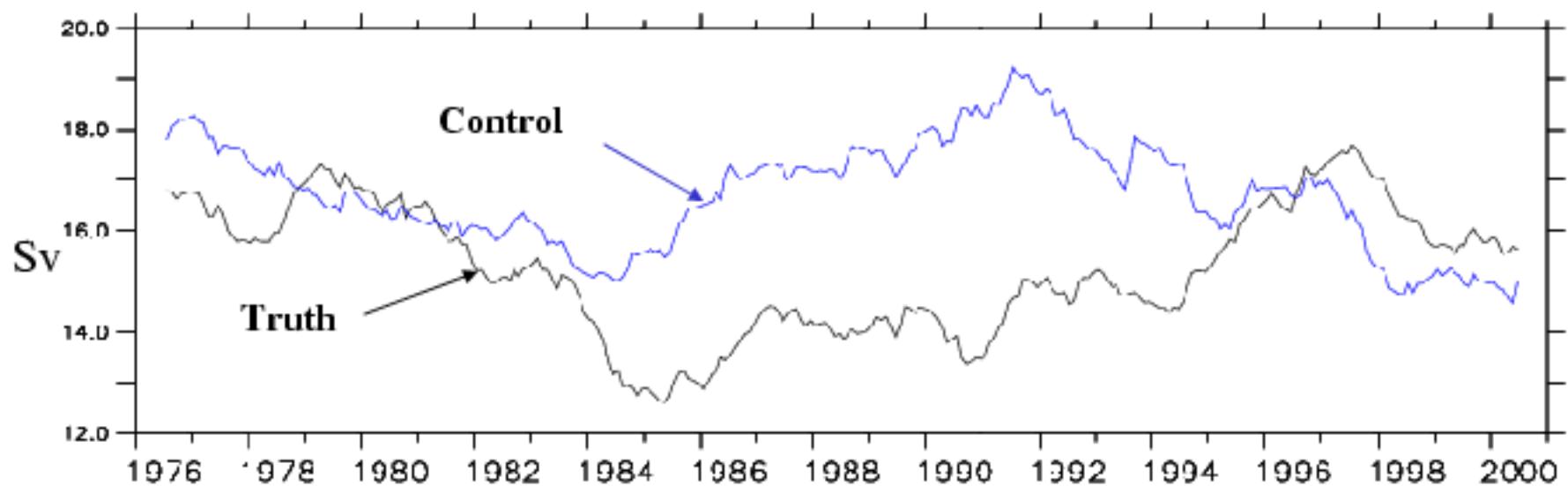
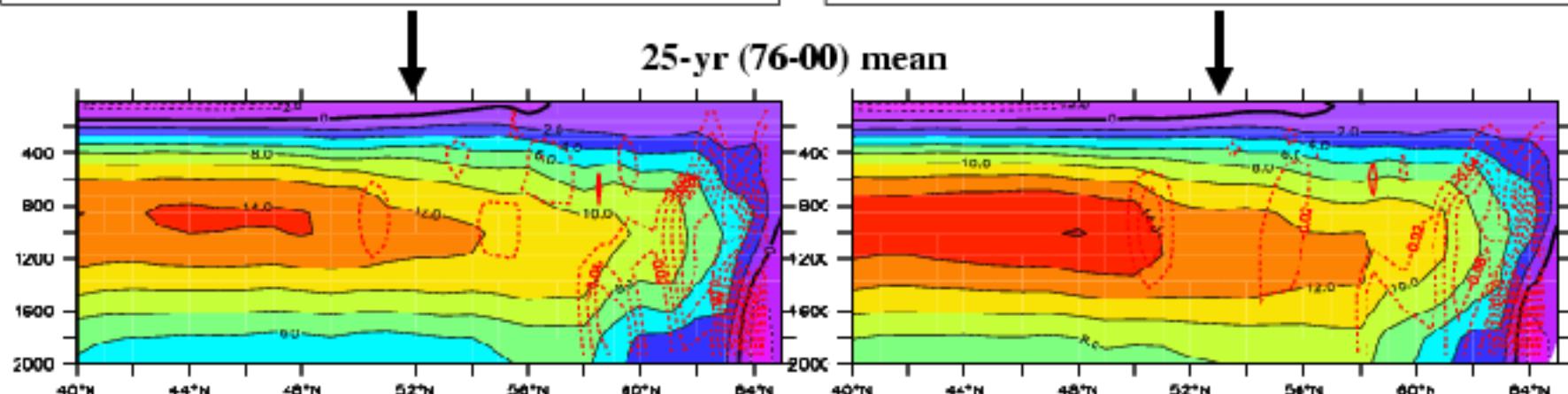


1860-fixed-year/temporally-varying GHGNA radiative forcing



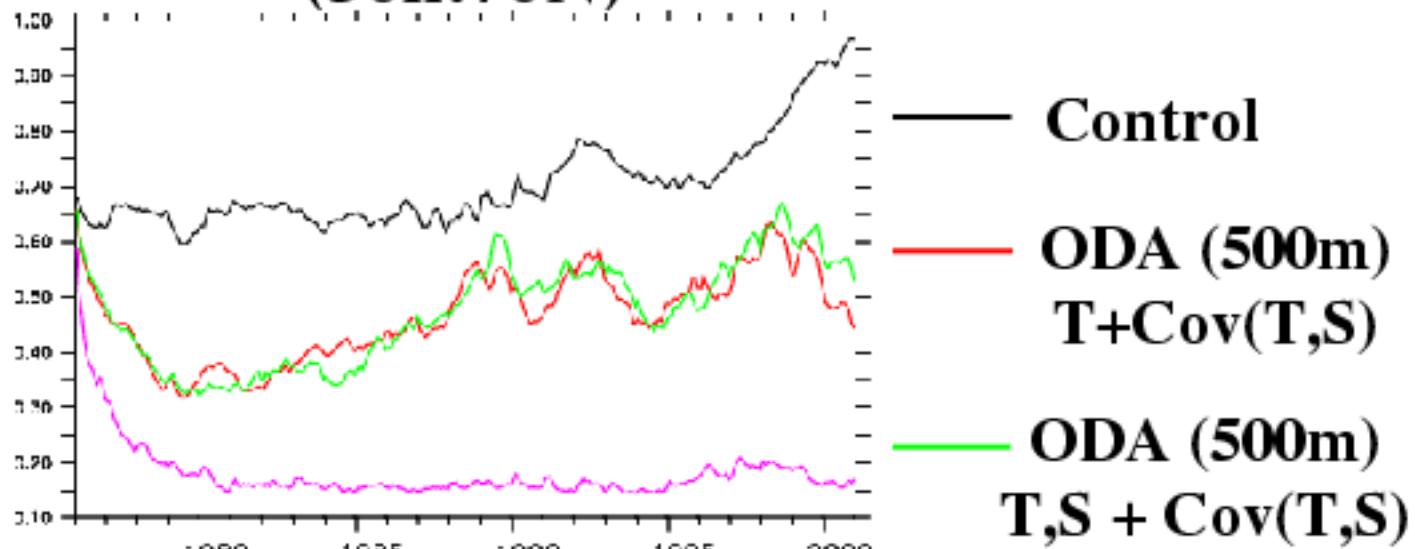
**Truth: Historical radiative forcing
run from 1861-2000, initializing
the model from 300-yr spinup
using 1860 radiative forcing**

**Control: Historical radiative forcing
run from 1861-2000, initializing
the model from 380-yr spinup
using 1860 radiative forcing**

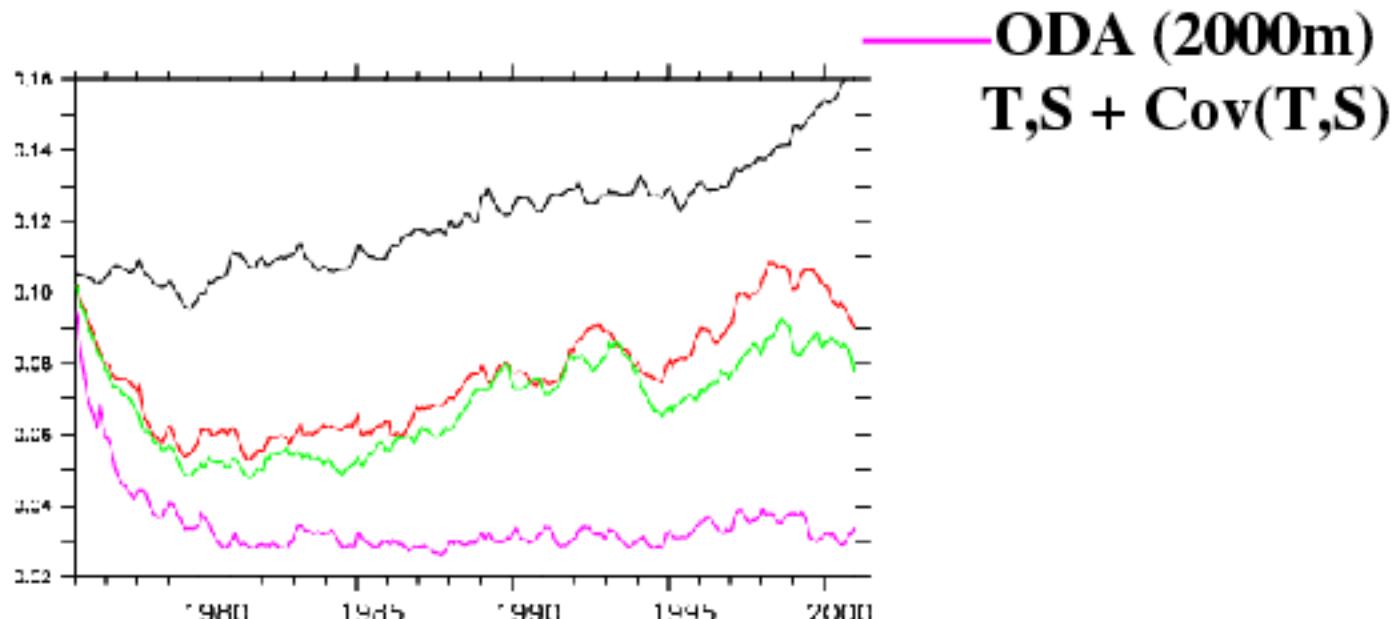


RMS errors of top 2000 m north Atlantic (30°N:70°N)

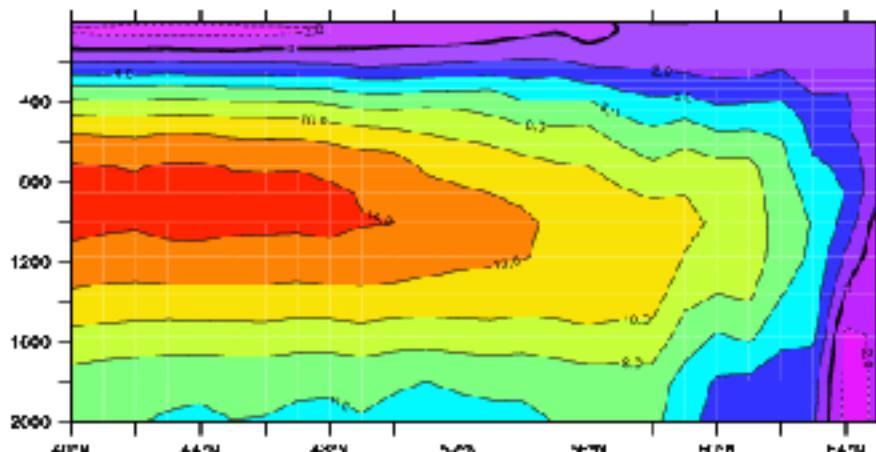
Temperature (°C)



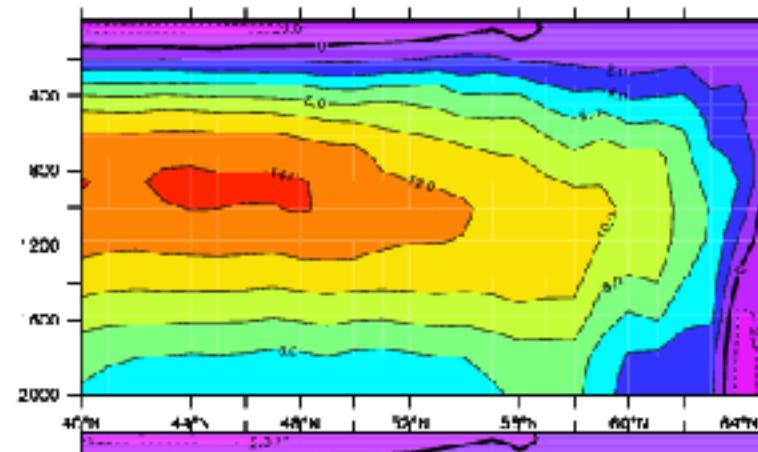
Salinity (psu)



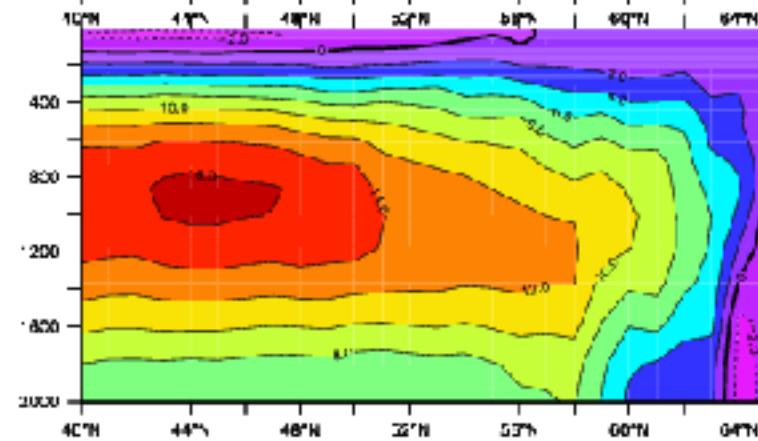
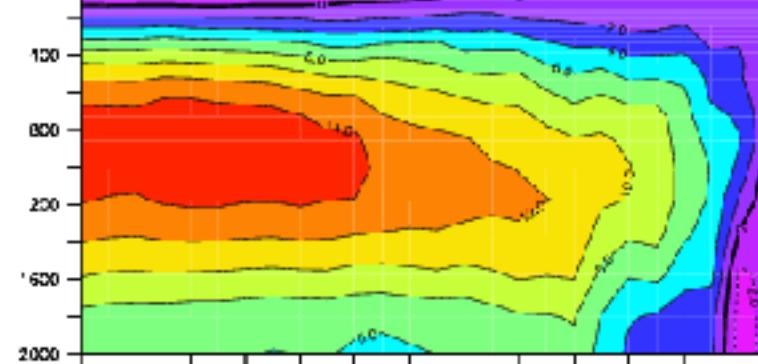
25-yr Time Mean of the Atlantic MOC



ODA (2000m)
T,S + Cov(T,S)

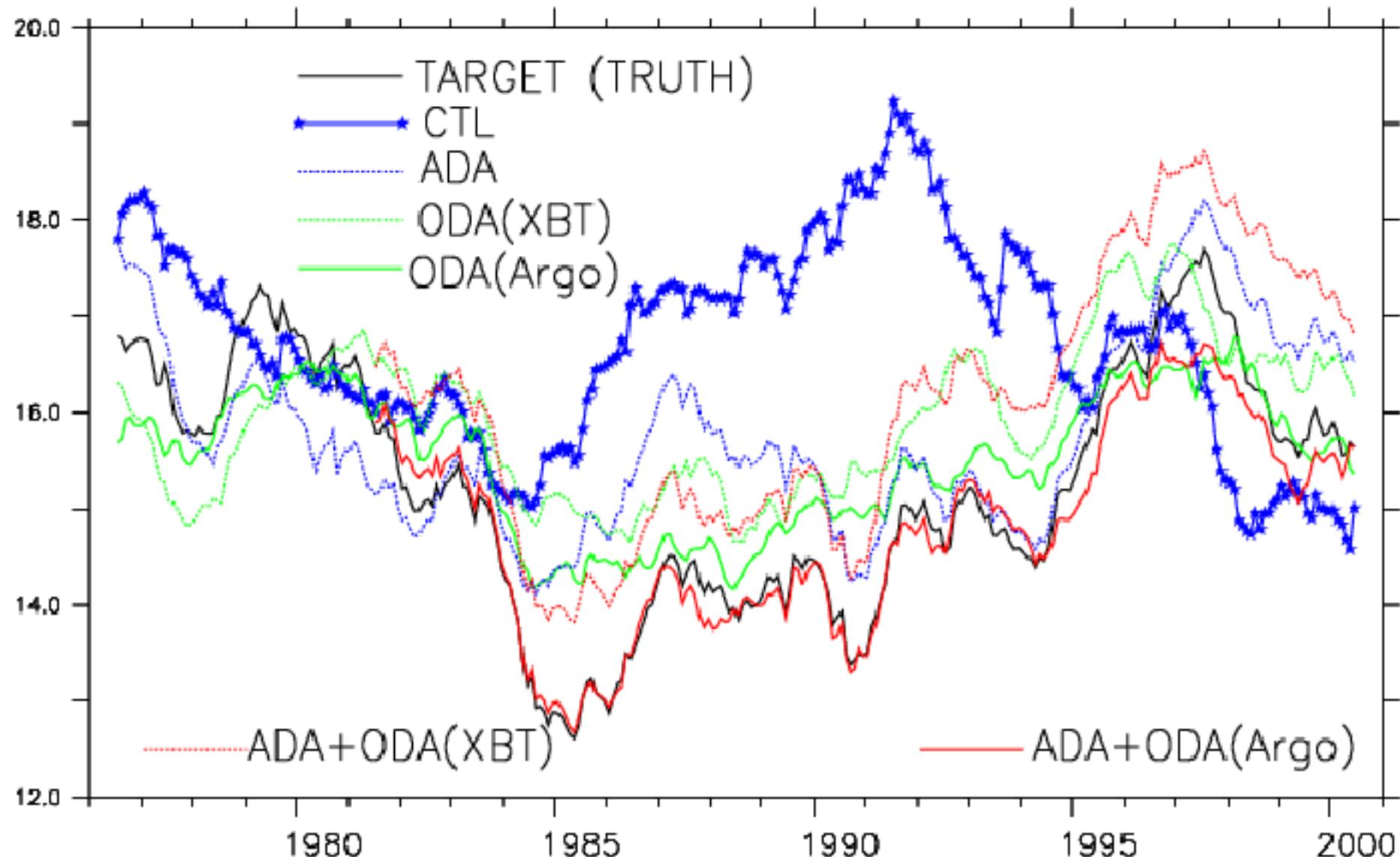


Truth
ODA
(500m)
T,S +
Cov(T,S)



ODA
(500m)
T +
Cov(T,S)

Estimation of NA MOC (Max(ψ) in (40n,70n)) by GFDL Coupled Data Assimilation System

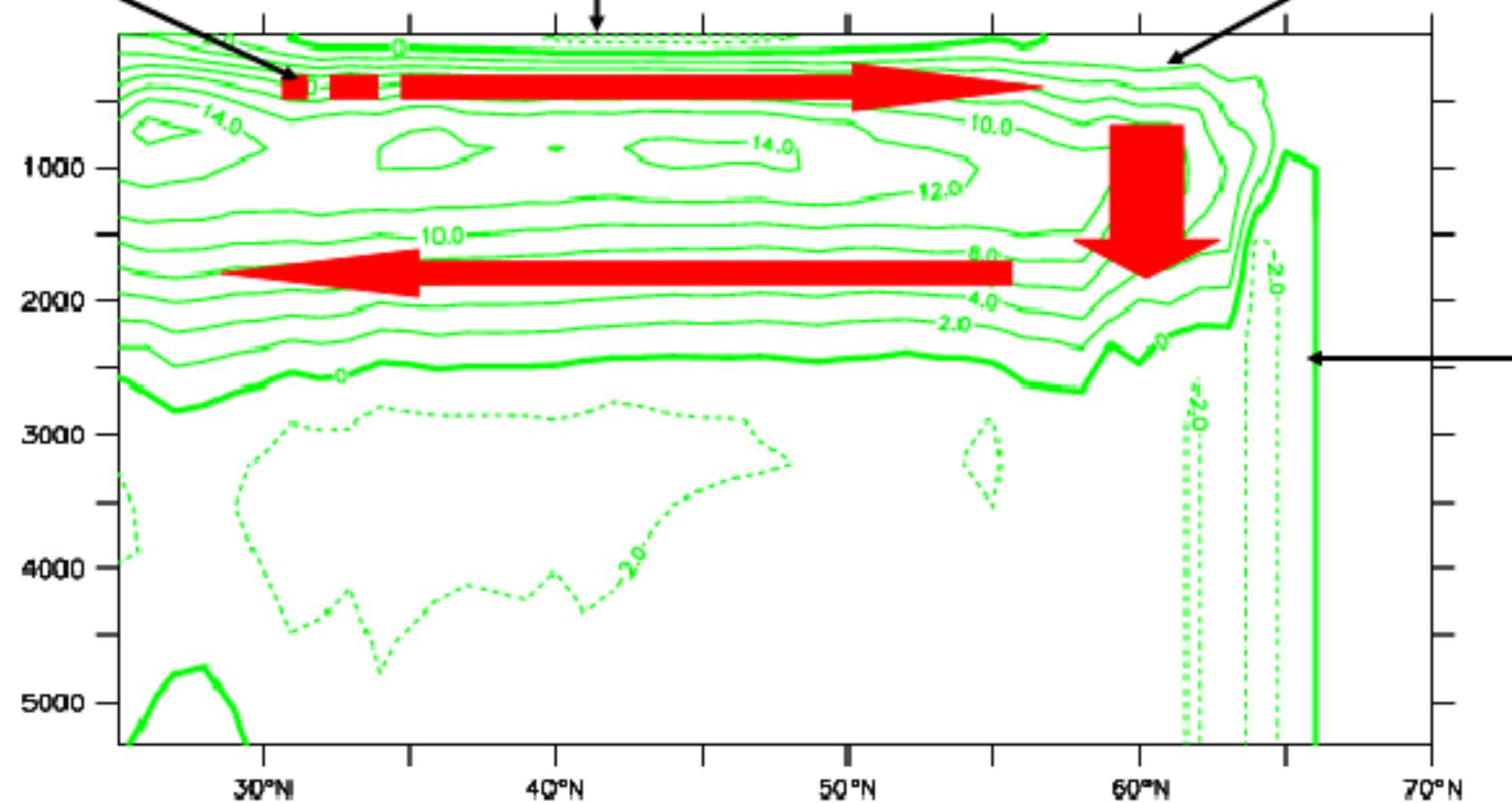


① THC's heat/salt transport

**② boundary forcing
from atmosphere**

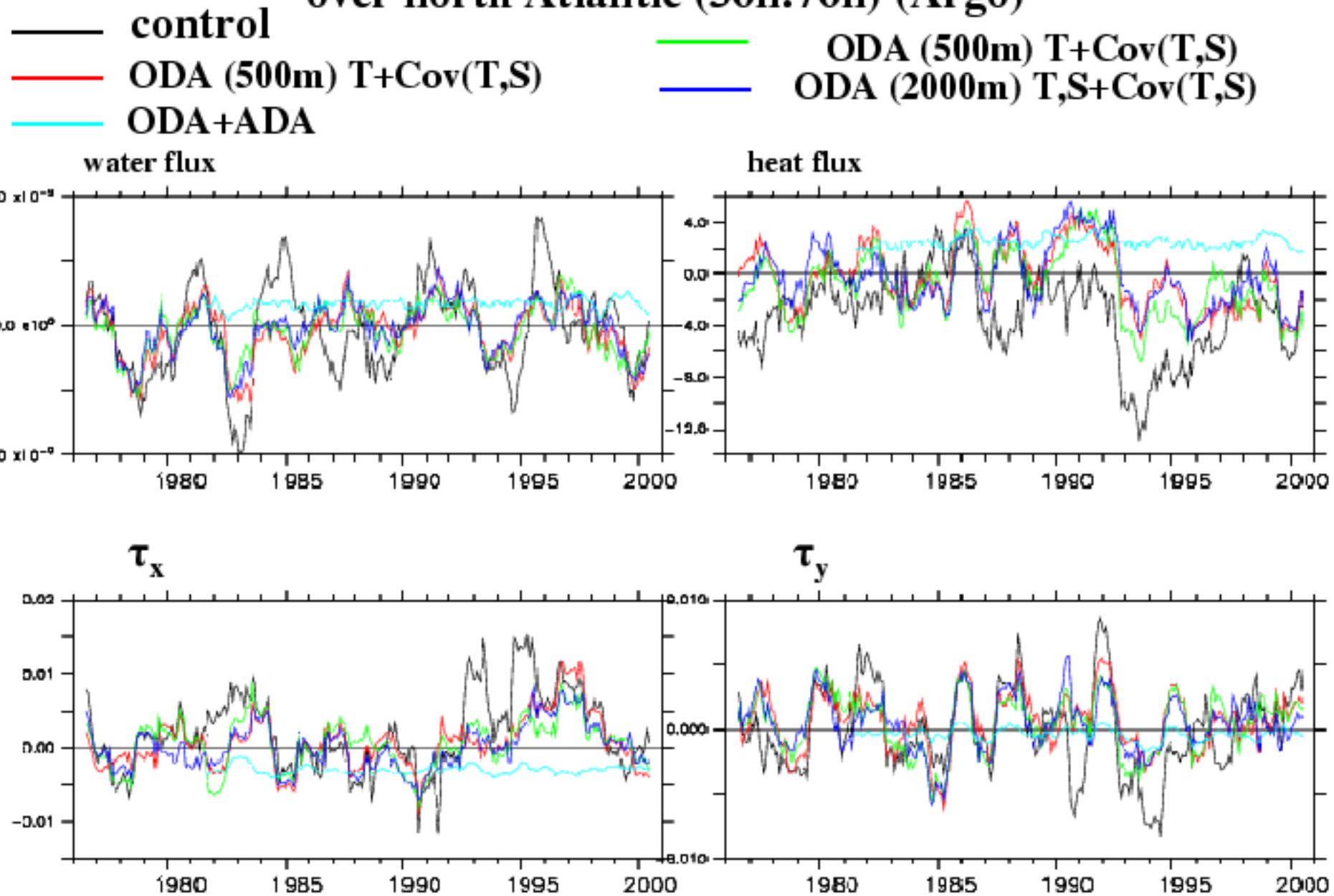
**④ Topography
processing**

**③ fresh water forcing
from ice & runoff**



Timeseries of regionally-averaged errors

over north Atlantic (30n:70n) (Argo)



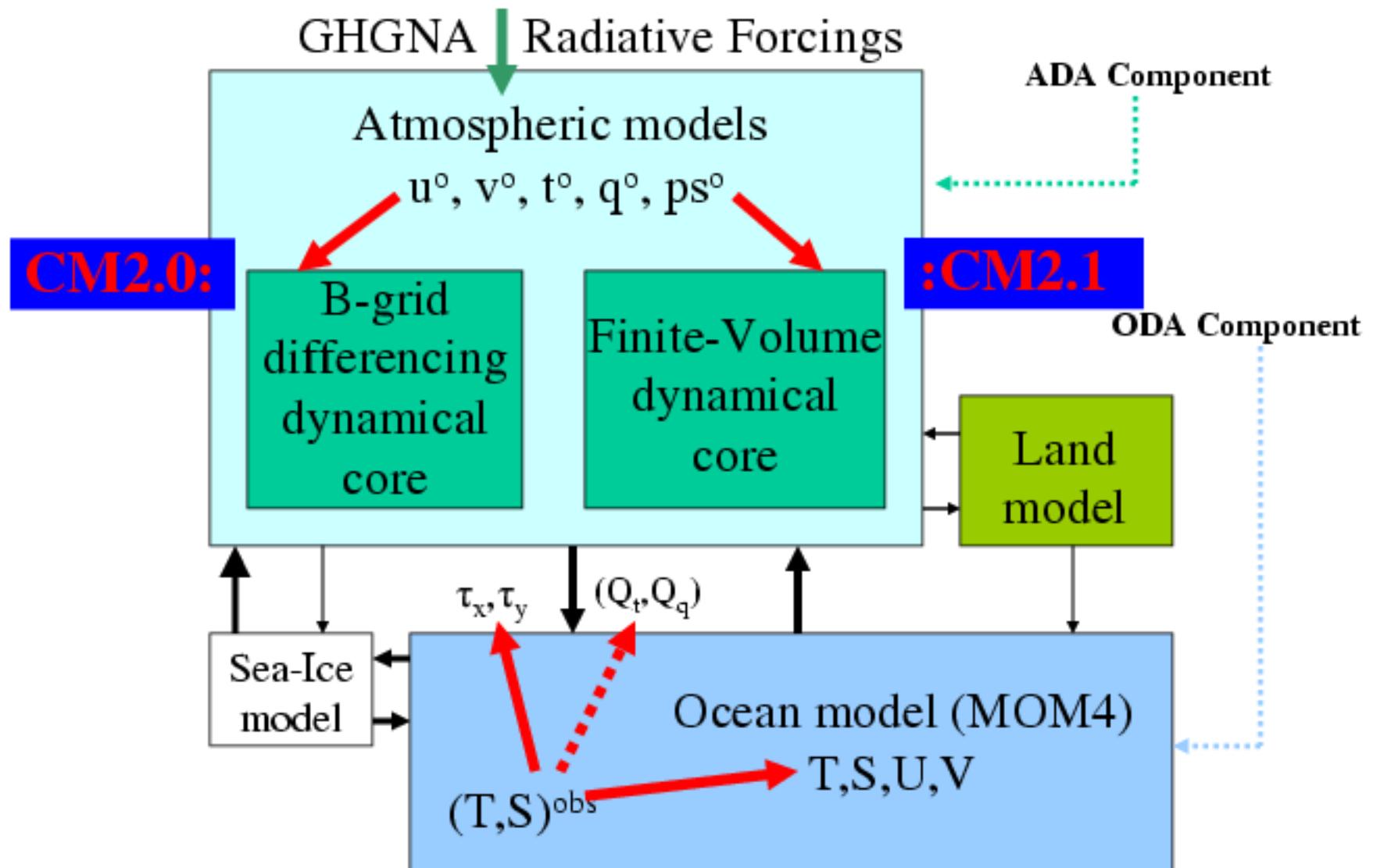
Summary on Impact of Oceanic Observing System

- ✓ Salinity observations in Argo network are extremely important to determine the NA thermohaline structure which is a leading order factor for estimating NA MOC.
- ✓ The 2km-depth of Argo observations is very important to estimate the structure of NA deep convections.
- ✓ The variability of NA MOC is associated with large-scale THC's heat/salt transport, sea surface forcing from atmosphere, fresh water forcing from ice and runoff and their interaction with the NA topography. Thus, besides oceanic data constraint to construct the large time scale phases, the correct sea surface forcing (atmospheric data constraint) is another key for capturing inter-annual variability of NA MOC.

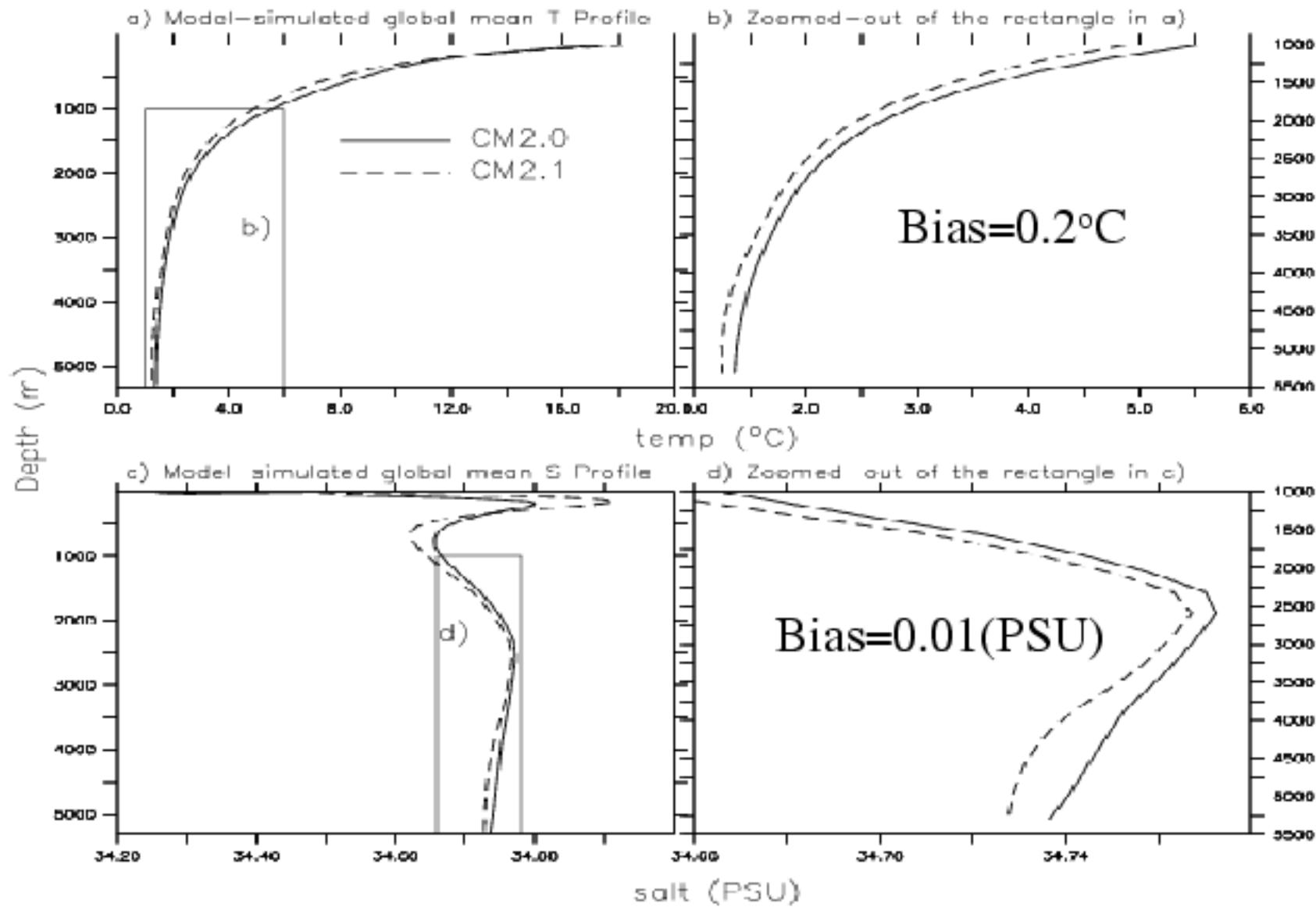
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GFDL's Ensemble Data Assimilation System Using Multi- Coupled Climate Models

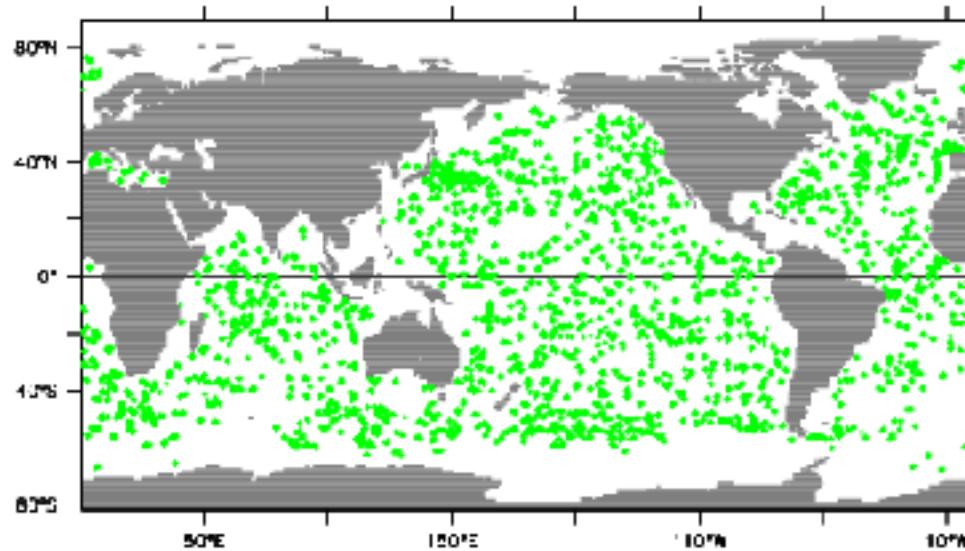


Two CGCMs 'Biased' Relative to Each Other

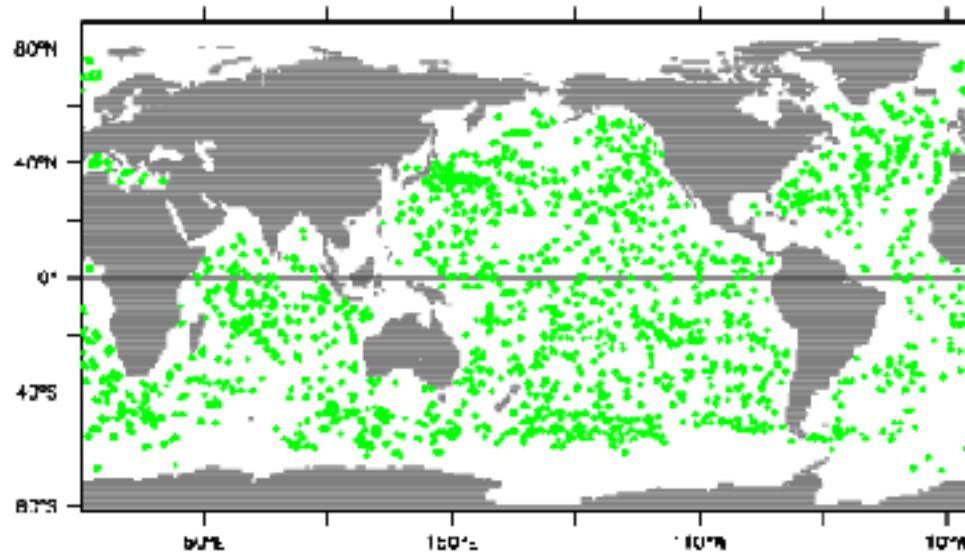


2005 June Argo network

Temperature

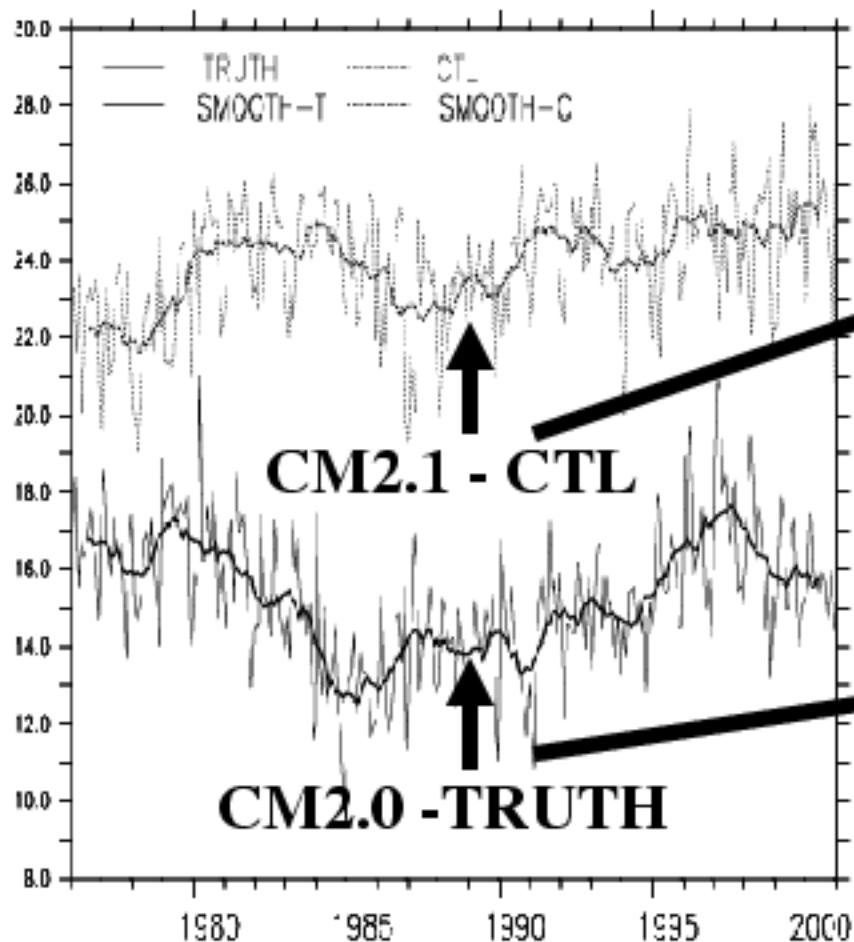


Salinity



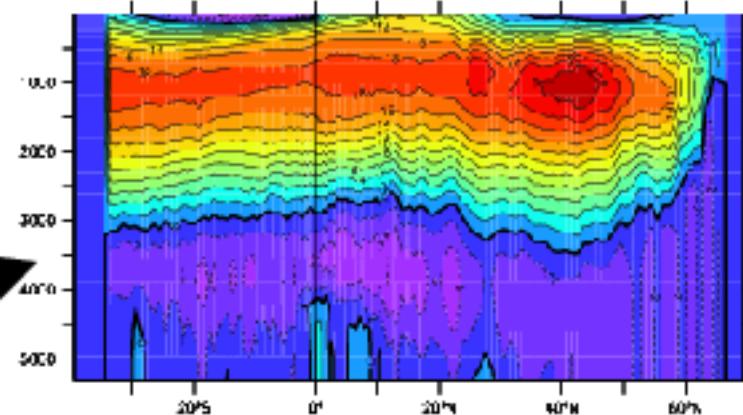
Different Meridional Overturning Circulations in two CGCMs

Timeseries of Max (ψ) at NA

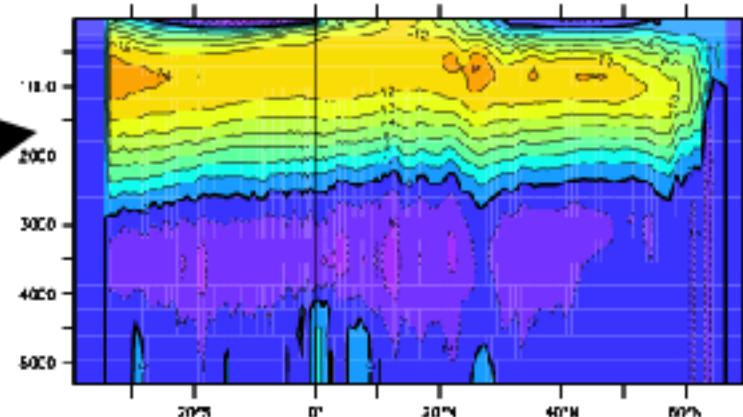


Time Mean of ψ

a) NA MOC stream function in CM2.1 IPCC (CTL)

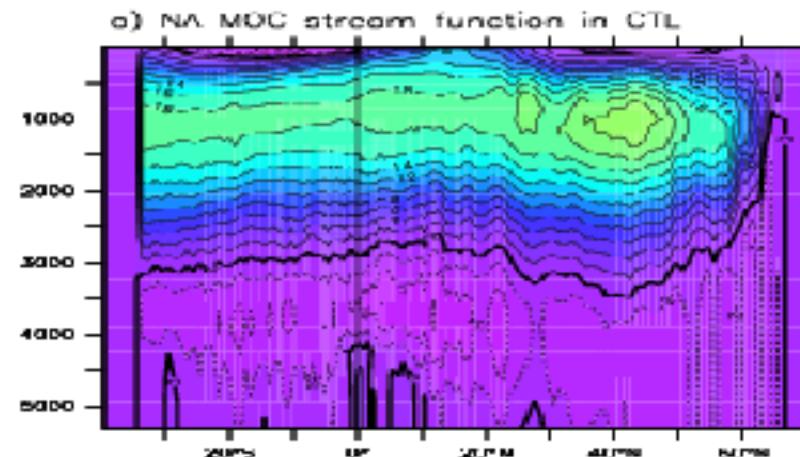


b) NA MOC stream function in CM2.0 IPCC (TRUTH)

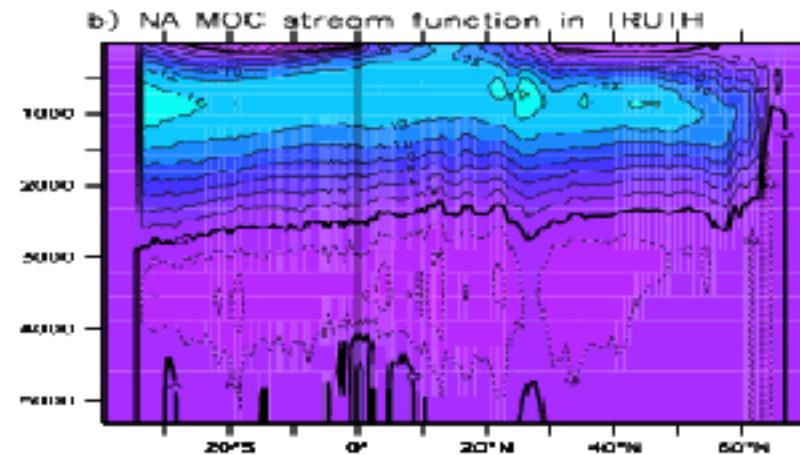


What is NA MOC estimated by ENSF in a ‘biased’ case?

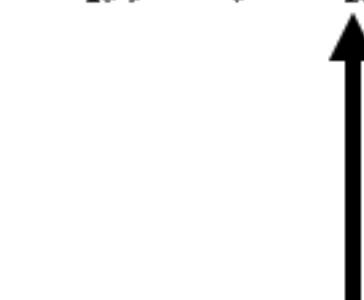
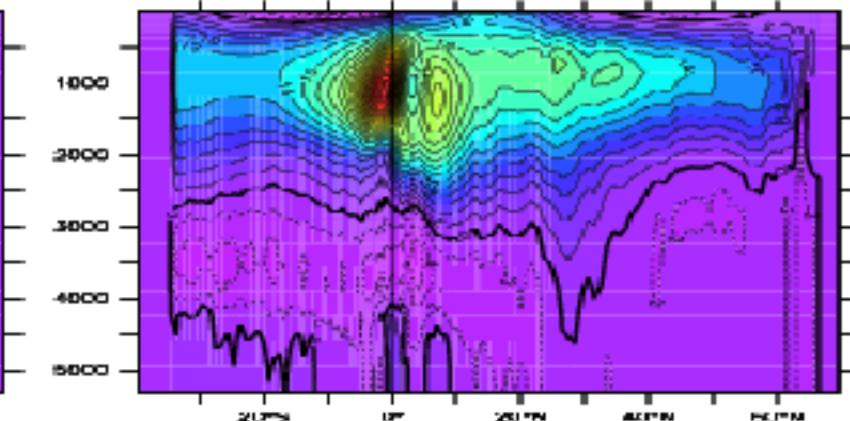
CTL



TRUTH



c) NA MOC stream function in ENSF



ENSEMBLE FILTER ODA
(ENSF)

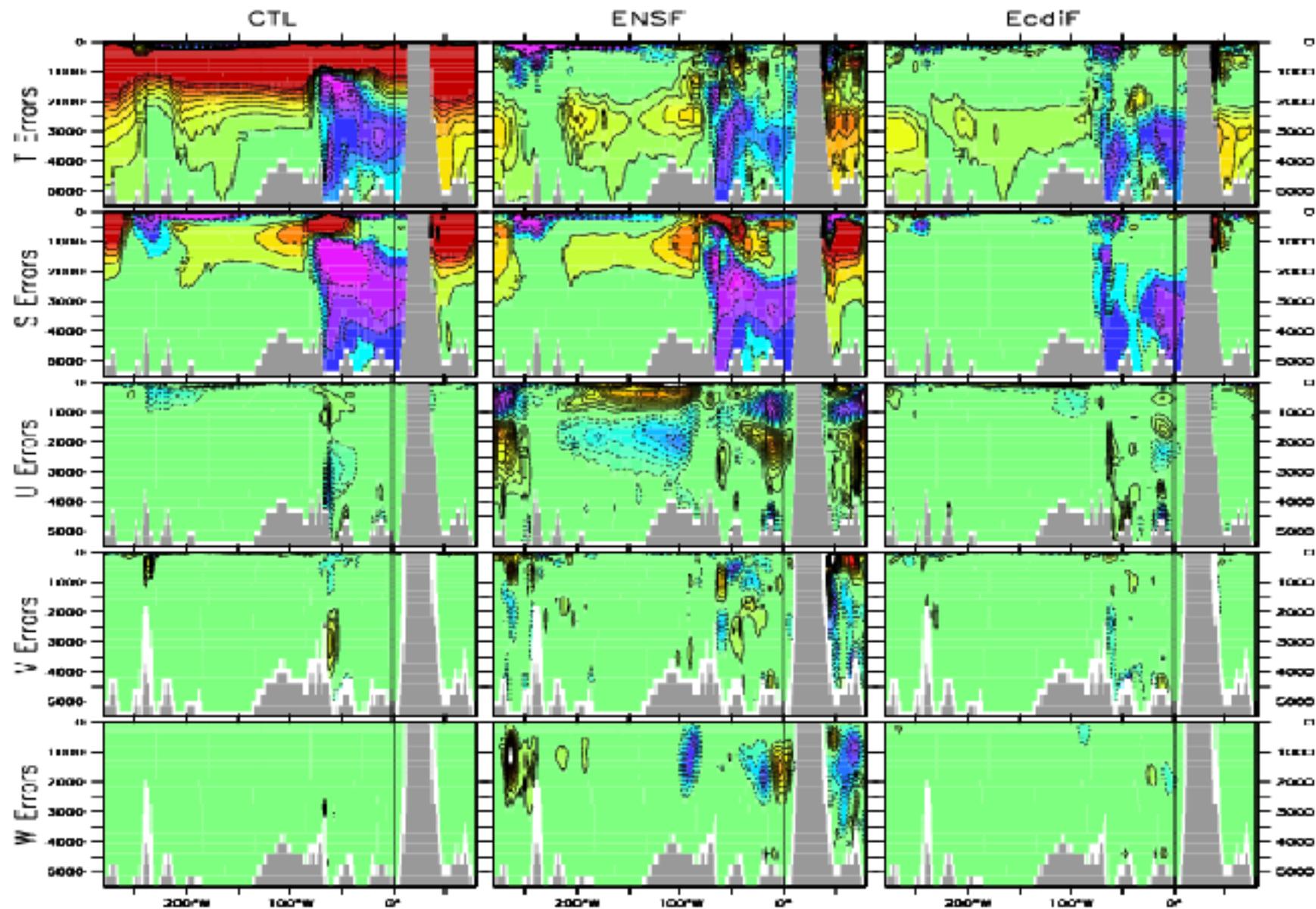
Challenges of Oceanic Data Assimilation with a **biased assimilation model**

- ✓ In deep oceans, bias is always larger than intrinsic variability.
- ✓ Finite ensemble size and model integration time cannot provide a correct estimate for deep ocean's low-frequency variance.
- ✓ Ensemble-based regression and limited obs depth cause **inconsistency** between well-constrained upper and poorly-constrained deep oceans.
- ✓ Incorrect water mass's distribution generates **spurious currents and vertical motions**.

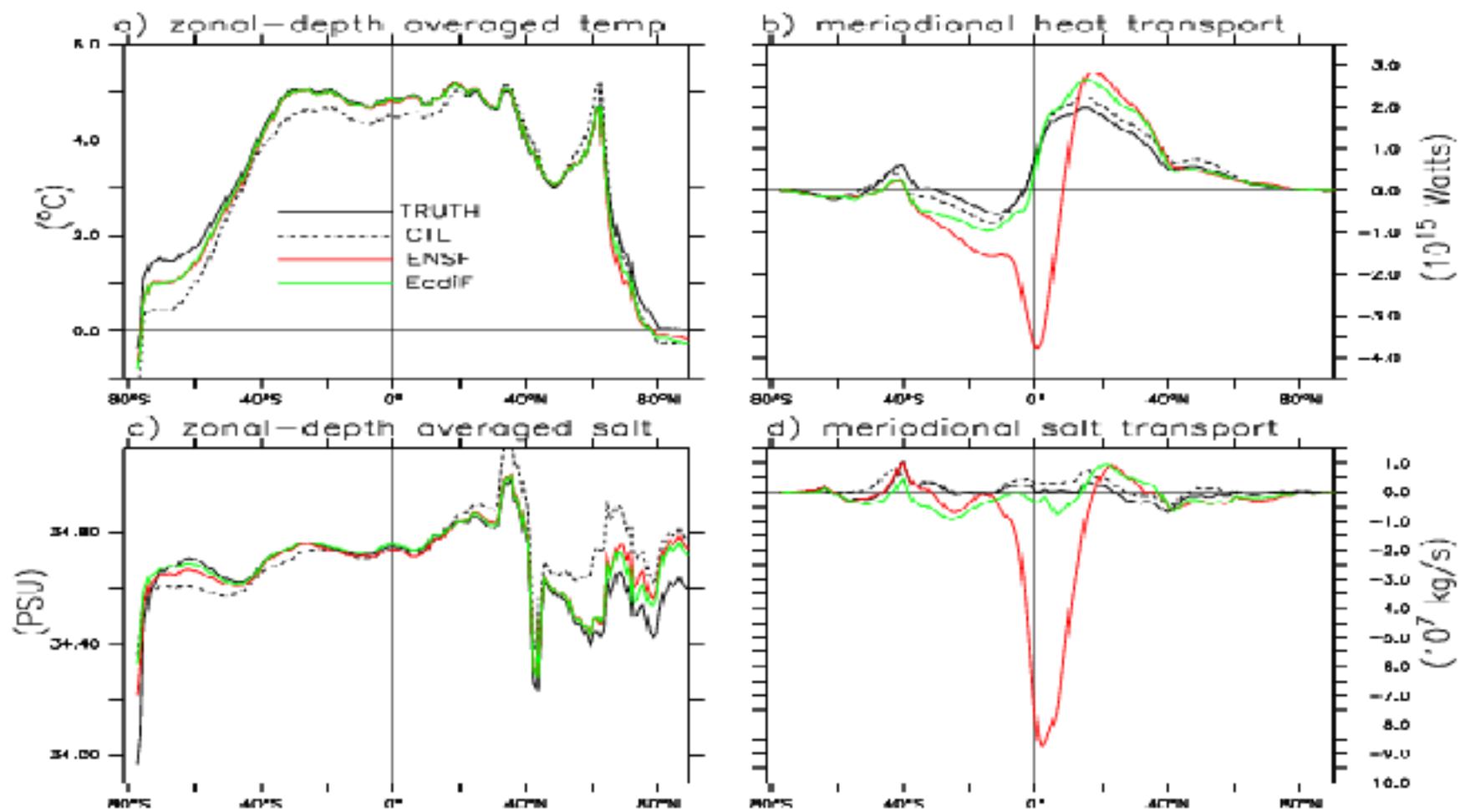
An improved algorithm — Ensemble Circulation-Dependent Inflation Filter (EcdiF) (press in MWR)

- ✓ Pre-computed anomalies' variance by a long time series of historical oceanic states improves the estimate of deep ocean's low-frequency variability.
- ✓ Combination of temporally-varying (ensemble-based) and time-invariate (pre-computed) covariances takes both high- and low-frequency variability account into regression.
- ✓ Signals at the bottom of observed profiles are coherently extended to deeper according to the local circulation's structure.
- ✓ Improved water mass's distribution generates much better estimates for currents and vertical motions.

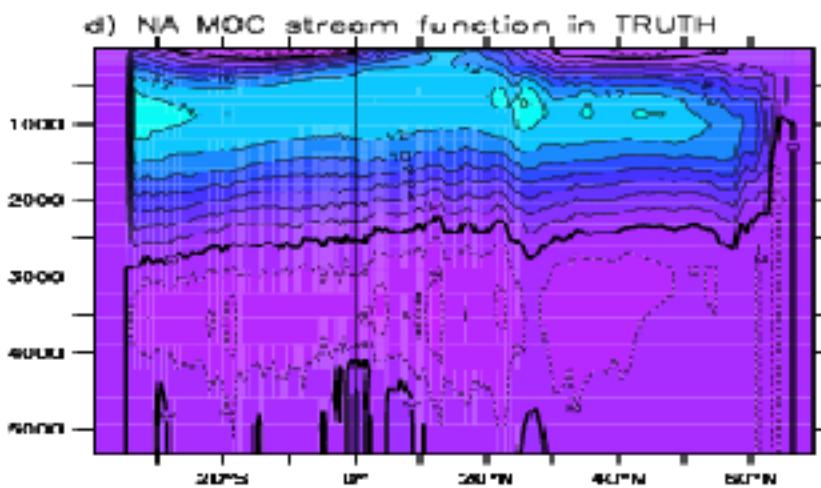
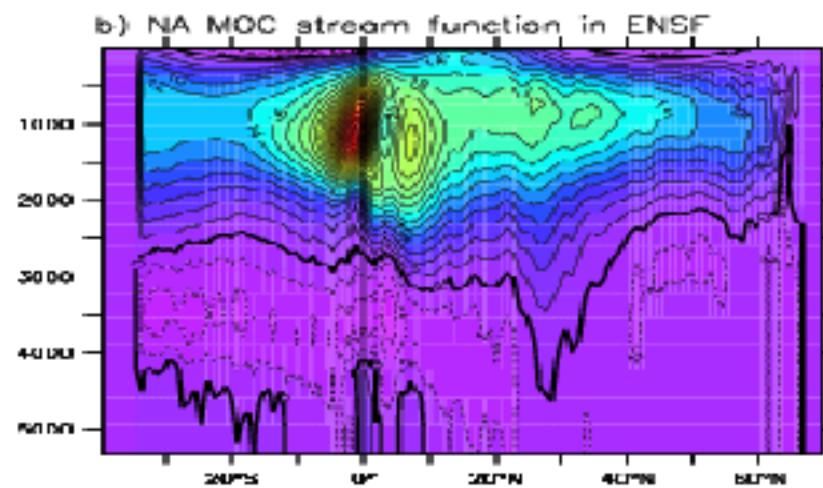
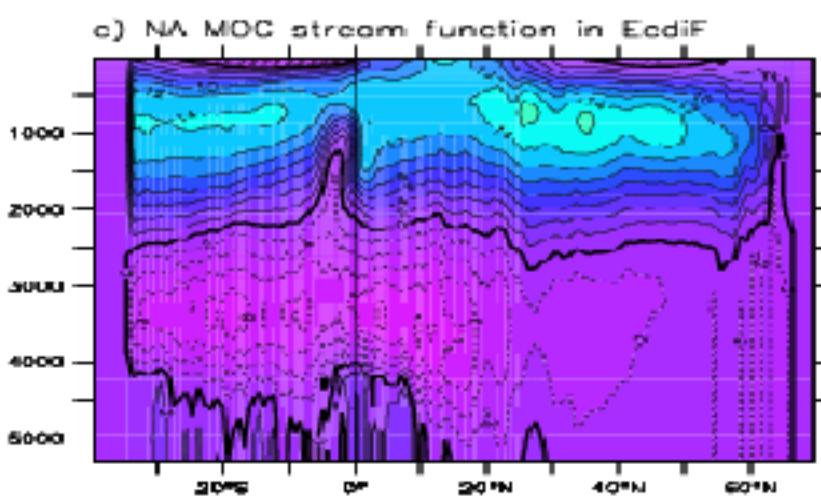
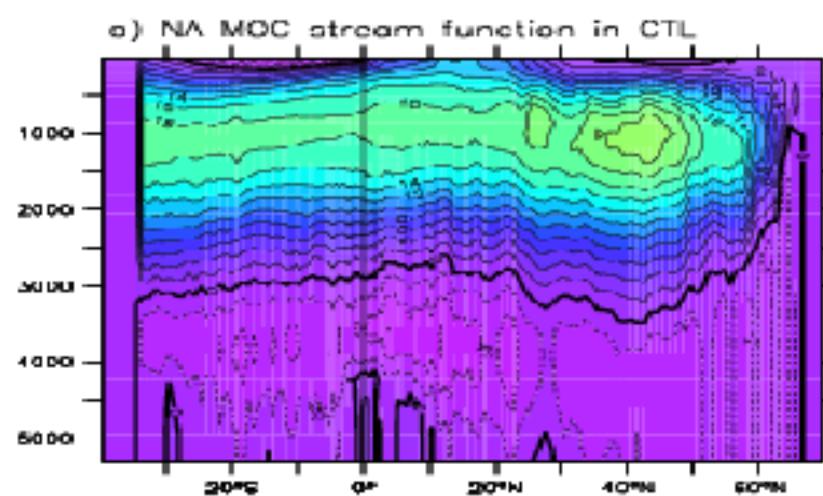
Assimilation errors in ENSF and EcdiF



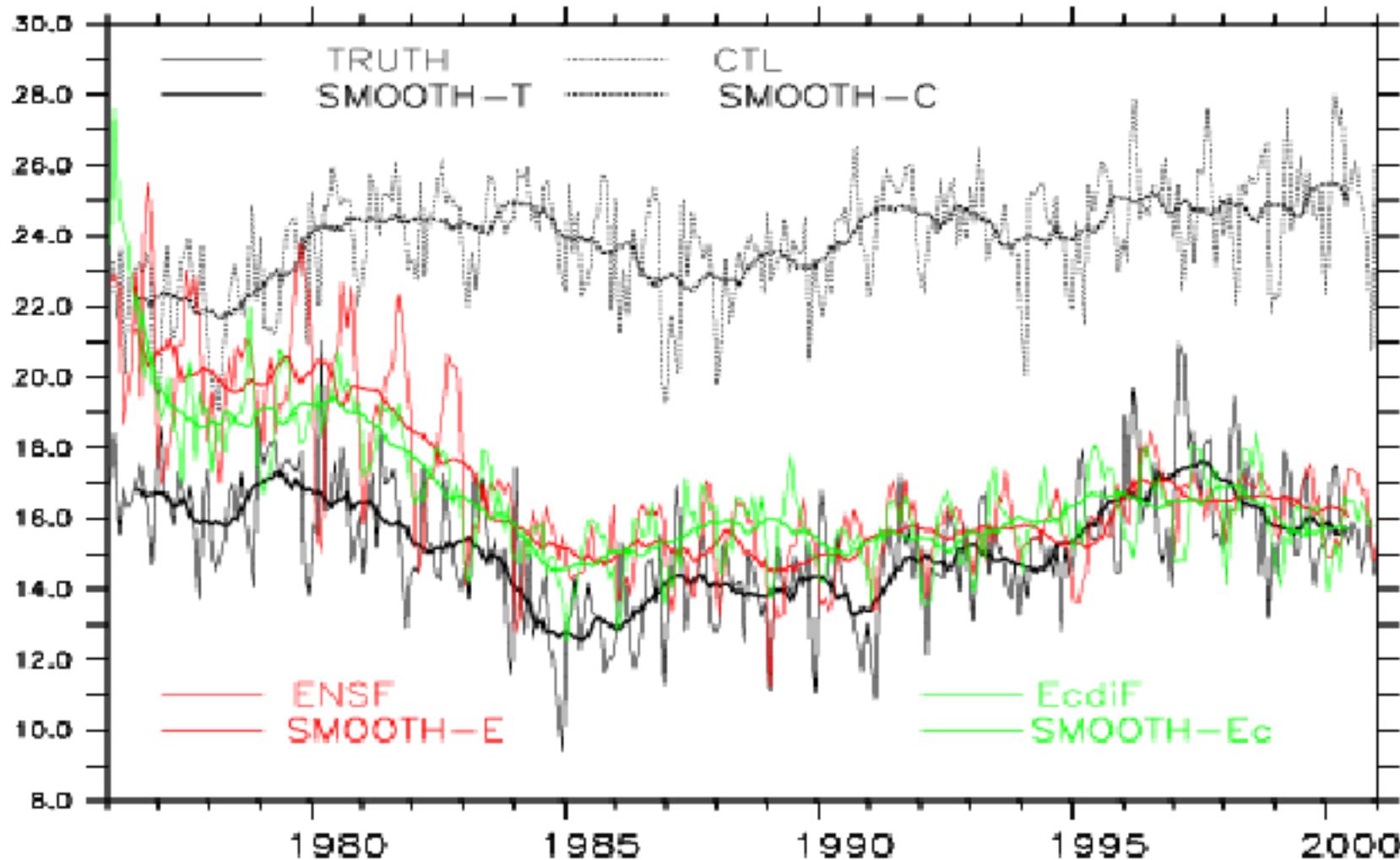
Heat/Salt transport



EcdiF



Time series of Max stream function of NA (40-70°N) MOCs



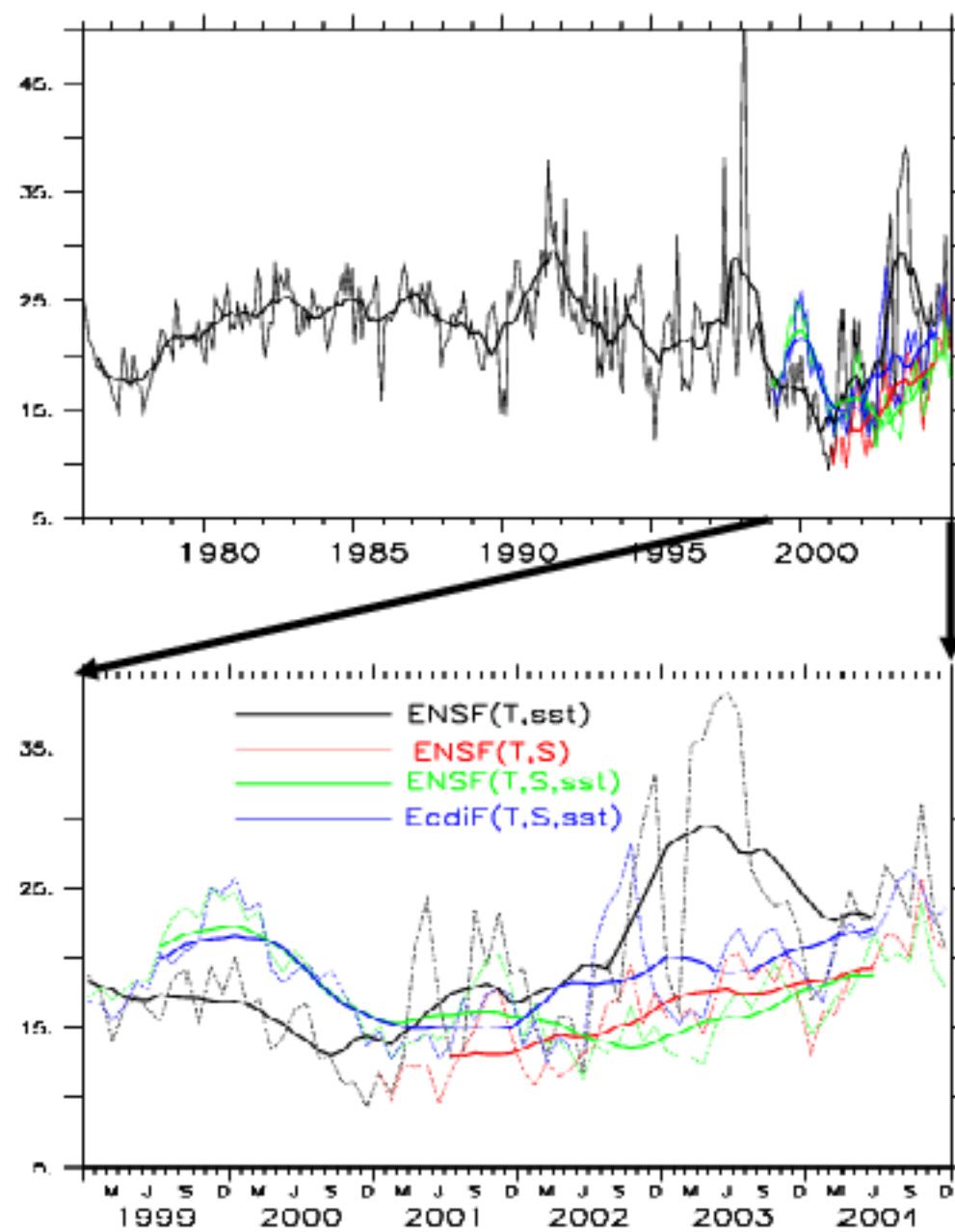
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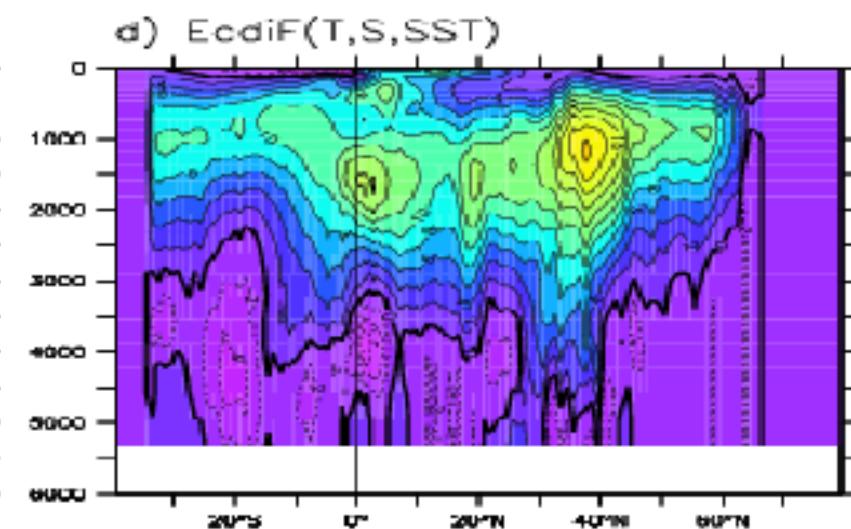
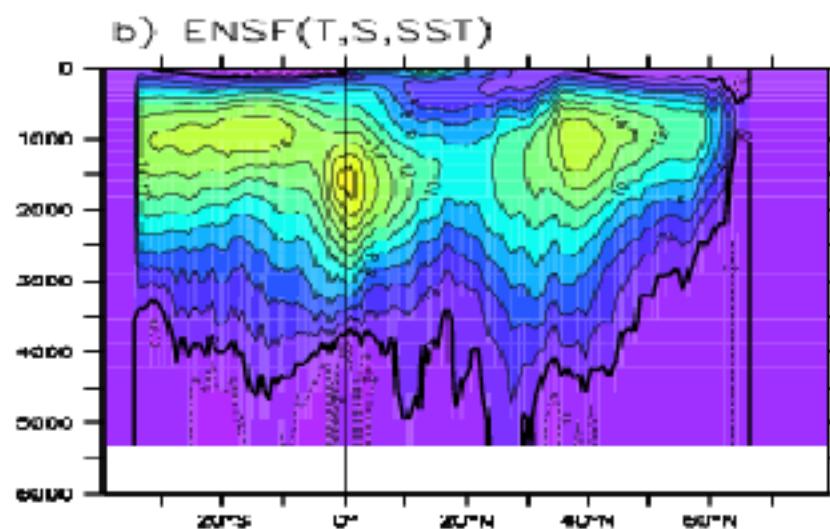
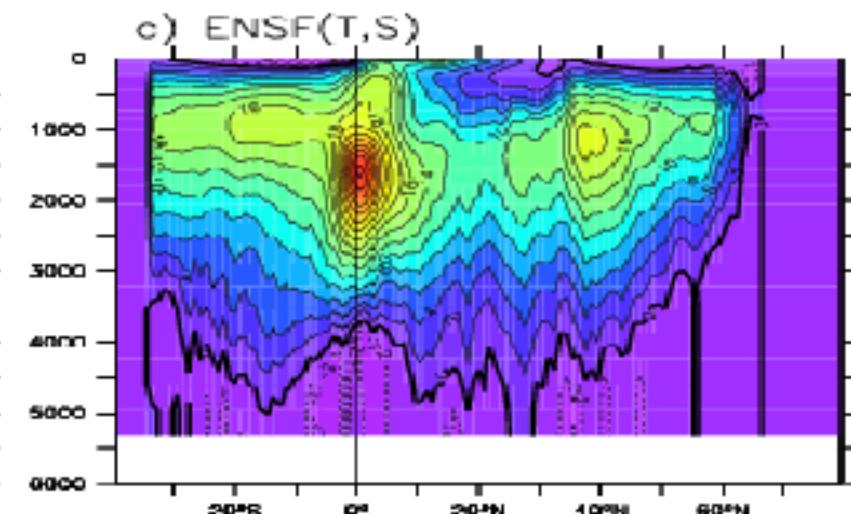
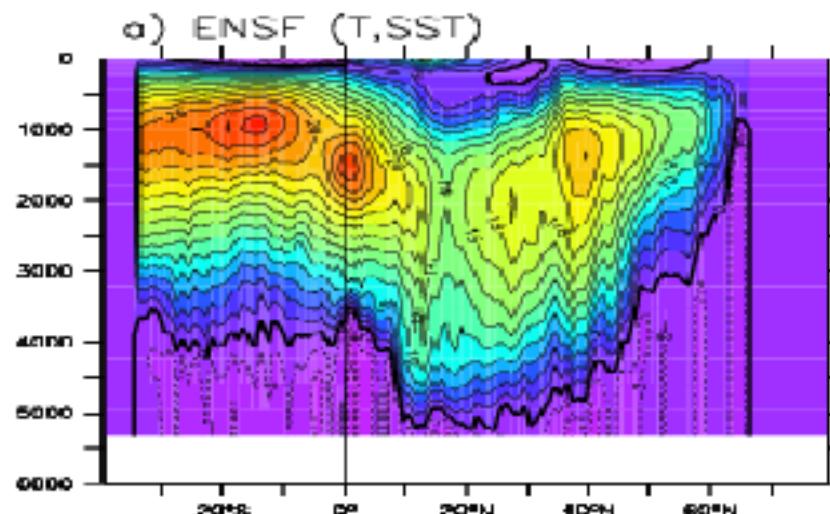
Data from 20th-/21st century observing system

- ✓ Ocean: Real-time oceanic observing network samples oceanic states
 - 20th-century: XBT, CTD, MBT, MRB, OSD, Gridded SST
 - 21st-century: Argo, XBT, MRB, Gridded SST, SSH
- ✓ Atmosphere: Gridded (NCEP/NCAR-reanalysis2) atmospheric variables sample atmospheric states
 - Wind: u,v
 - Temperature
 - Specific humidity

Time series of max value of NA MOC stream function

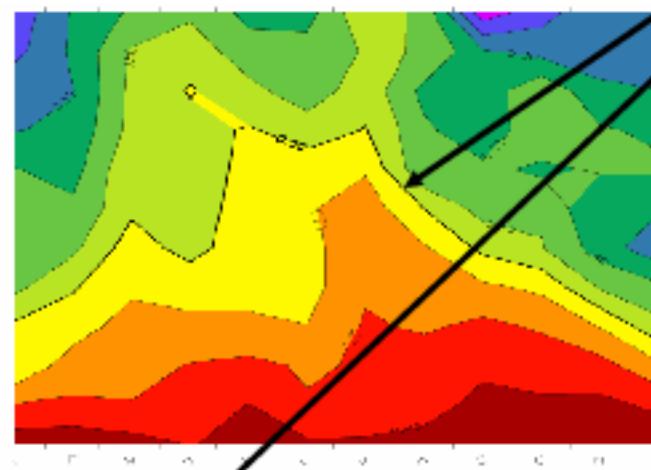


NA MOCs (03-04 Time Mean) estimated in 4 schemes using real data



NINO3 SST forecast skills

Anomaly Correlation

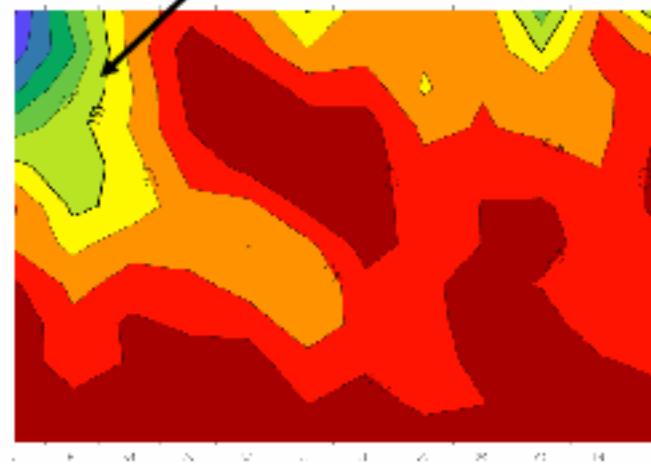
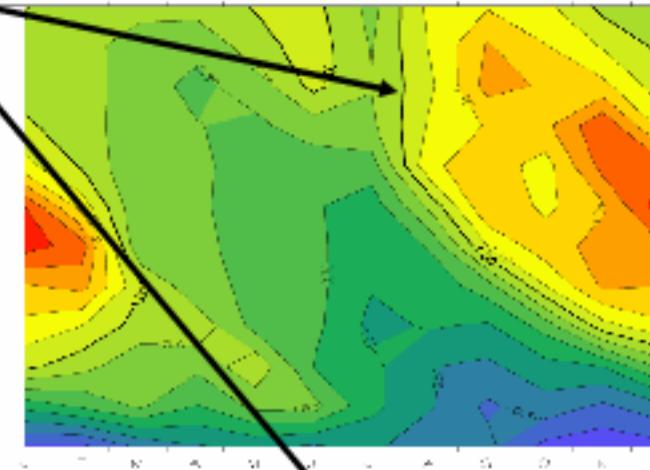


0.6

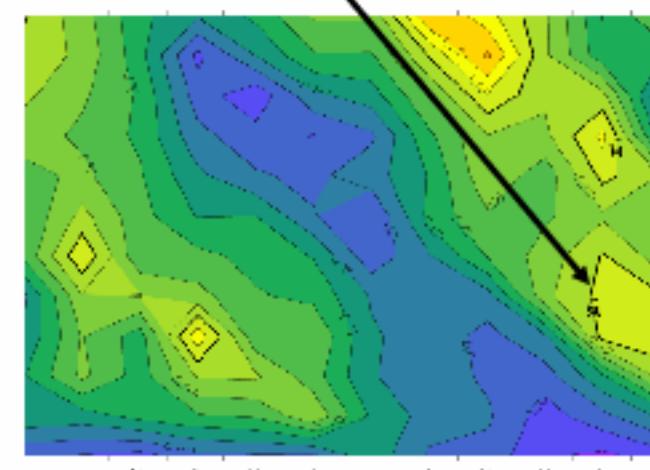
3Dvar

1.0

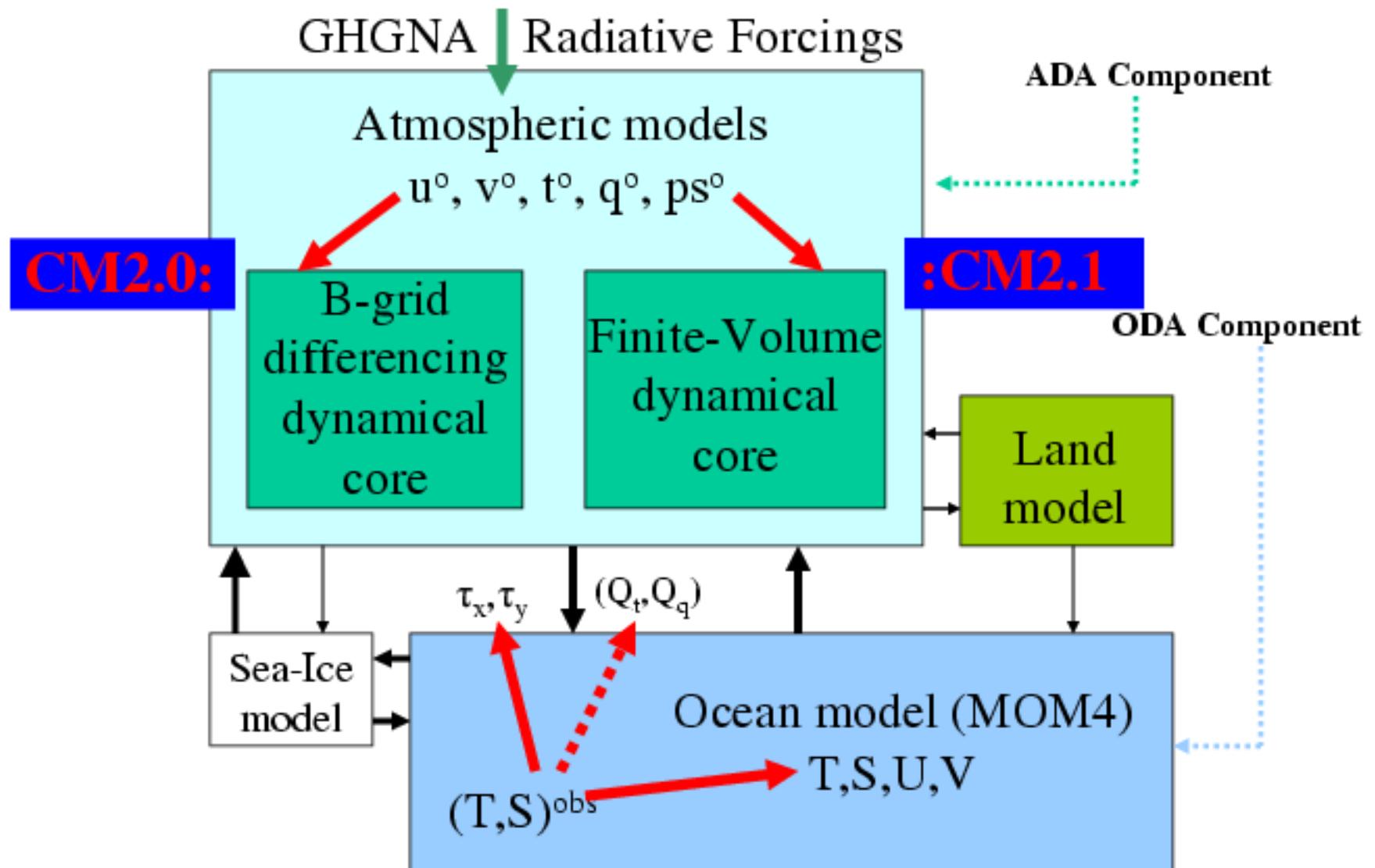
norm RMS errors



ENSF(T,sst)



A Multi-Model Ensemble Data Assimilation System at GFDL



Long Term Efforts ...

- ✓ Improve climate variability analysis (Carbon/heat uptake, circulation, ...)
- ✓ Establish a prototype forecast system (SI, decadal/multi-decadal)
- ✓ Detection of climate change
- ✓ Analysis estimate of variables in sea ice and land model (ice mass, run-off etc., for instance)
- ✓ Observing system evaluation/design
- ✓ Optimal choice for ensemble forecasts
- ✓ Model evaluation/verification for improving modeling
- ✓ Model parameter estimation